MASTER

Indoor environment of sleeping rooms and sleep quality

a research on the influence of carbon dioxide levels on sleep quality in an intervention study

van Ruitenbeek, A.M.

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Department of the Built Environment

Navigation address: De Zaale, Eindhoven
P.O. Box 513, 5600 MB Eindhoven
The Netherlands
www.tue.nl

Author
A.M. van Ruitenbeek

Supervisors
Prof. Dr. H.S.M. Kort
Dr. Ir. M.G.L.C. Loomans
Ir. K. Grooten
Ir. A. Mishra

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Where innovation starts

1 Preface

This report has been written for the graduation project of Aike van Ruitenbeek in the master track Building Physics and Services at the Eindhoven University of Technology.

It consists of a paper on the research that was conducted, and a few appendices. The paper discusses a brief introduction, the methodology, the results, which are discussed later, and a conclusion is given. The appendices give further information about the method and results.

A few persons should be thanked for their help and support during this project. Firstly Helianthe Kort, Marcel Loomans and Karin Grooten, my supervisors, for their guidance during the project. Bart Cremers for introducing me to the subject and for providence of his expertise. Furthermore, I would like to thank Wout van Bommel and Marcel van Aarle who helped me with the measurement equipment in the BPS laboratory. Additionally I would like to thank all the students, who amongst others voluntarily gave up any alcoholic consumption five days, who participated in the study, without their participation this study would not have succeeded. I would like to thank Asit Mishra for helping me understand the statistics. Finally, Manon Derks, who gave up many hours of her time to help me with the Matlab script and all the people who reviewed the report with a critical eye.

2 Article

Abstract

In this study the indoor environmental quality of bedrooms was examined, specifically indoor air quality indicated by carbon dioxide (CO_2) levels, and its effect on the sleep quality. Additionally a threshold from which sleep quality starts to get impaired is tried to be established and different methods for measuring sleep quality are examined. For 17 single rooms the CO_2 levels, temperature, background noise and relative humidity were measured for five days for two cases: 1) measurement with open window or door, and 2) measurement with closed window and door. 17 Subjects were selected initially by building type and later with a selection questionnaire. A questionnaire and a sleep diary were filled in every morning to measure the qualitative sleep quality. A Sensewear Armband was worn on the upper arm at nights to measure the metabolism to obtain the quantitative sleep quality. Additionally a flex sensor was used to detect movement during sleep. SPSS was used to analyses the data with Pearson and Spearman Correlation and the Linear Regression Analysis to establish univariate and multivariate correlations. The average CO_2 level for the open window condition had a value of 731 parts per million (ppm) and the average CO_2 level of the closed window condition had a value of 1147 ppm. It was concluded that the depth of sleep, measured by the questionnaire, was significantly different between the two conditions: lower CO_2 levels and higher temperature correlate to a deeper sleep (P-value = 0.008). It was noticed from the Sensewear Armband that the number of awakenings tend to decrease with lower CO_2 levels and higher temperatures (P-value = 0.005), while sleep efficiency improves (P-value = 0.001). Furthermore, from a CO_2 level of 800 ppm and upwards, the depth of sleep and sleep efficiency is lower than below 800 ppm, and the number of awakenings is higher. As some of the sleep quality variables were additionally affected by the room temperature, it is suggested for future research to choose the opened door setup over the opened window setup and keep the building characteristics similar for all subjects. Although the questionnaires did not seem to show the same mean values as the Sensewear data, the results did show highly significant correlations. The flex sensor showed inconclusive results, but could be promising with a better set-up.

Introduction

Humans generally spend seven to nine hours asleep per day and about one third of life is spent asleep. Sleep has an important impact on health and work performance during the day. The department of Sleep Medicine at Harvard Medical School discusses the importance of sleep, such as preservation of energy, brain development, memory processing and learning. Many studies show that the indoor environment quality (IEQ) influences the quality of sleep (Van Hoof et al., 2009). A few factors that are known to influence sleep are temperature, light and background noise. A bad indoor air quality, often indicated through high carbon dioxide (CO_2) levels, has in many studies shown to have negative effect on health and performance. Sick Building Syndrome (SBS) symptoms additionally seem to occur with higher CO_2 levels (Logue and Sherman, 2011). Although much research can be found on indoor air quality and health and performance, little can be found on the effect of indoor air on sleep. This research will therefore elaborate on the effect of air quality on sleep. Although Dutch regulations require a CO_2 level below 1200 parts per million (ppm), to obtain a proper indoor air quality, CO_2 levels of 800ppm for healthy adult and a levels of 600ppm for people with health conditions are to be strived for to prevent health problems of the airways (Roelofsen, 2012) (NEN 1087). However, Bekö et al. (2010) noted that 57% of 500 children's bedrooms in Denmark do not meet the requirements of 1200 ppm. Only a few studies can be found about the effect of CO_2 levels in bedrooms on sleep. Laverge et al. (2011) and Strøm-Tejsen et al. (2014) both carried out a study where sleep quality was measured in a situation with a high CO_2 levels (Strøm-Tejsen 2395 ppm, Laverge 3000 to 4500 ppm) and a low CO_2 levels (Strøm-Tejsen 835 ppm, Laverge 1000 to 2500 ppm). Both studies found a relation between sleep quality and CO_2 levels, where lower levels showed an improved physical or subjective sleep quality. In a study by Cremers (2015), the carbon dioxide (CO_2) levels in the bedroom of a dementia patient were measured by the caretaker, reporting when she was showing restless behavior. At CO_2 levels above 800 ppm the restlessness seemed to increase. Although this study only shows the results for one person, the found correlation is strong enough to warrant further research.

In this paper the results of this study are presented. The aim of this study is to determine whether there is a relation between sleep quality and CO_2 levels in the bedrooms of healthy adults. If a correlation is found, the study additionally aims to find a threshold for a CO_2 concentration from which sleep quality starts getting impaired. Sleep quality is measured by different types of measurements, both quantitatively as well as qualitatively to examine how sleep quality can best be measured. The outcome can be used to set up a larger study to examine if indoor air quality can contribute to the improvement of the quality of sleep and life.

Methodology

A mixed method approach was used to study the sleep quality in two different environmental conditions. One condition was with an opened window or door, the other with a closed window and door. Measurements were executed to determine the CO_2 levels, temperature, background noise and relative humidity of the bedrooms. The sleep quality was measured by qualitatively measurements with the use of questionnaires. Additionally the sleep quality was quantitatively assessed by a Sensewear Armband and a flex sensor, through temperature and movement detection respectively.

Experimental design (subjects and environment)

As the available equipment and time was limited, 18 subjects were selected, initially by building type, to obtain similar building characteristics and later through an online questionnaire. However the data of one subject was eliminated from analysis because of a power outage. The demographics of the subjects can be seen in Table 1. The subjects did not use any sleep medication and did not suffer from any sleep disorders or have any other health issues that could affect sleep (e.g. recent operation, asthma). In addition, during the measurements the subjects were not allowed to consume alcoholic beverages, as studies show alcohol influences sleep (Singleton R. A., et al., 2009). Both conditions were measured for five days, with no change in amount of people or furniture in the room. The subjects were situated in seven different buildings in Eindhoven indicated in the table with a letter. The building characteristics can be seen in the appendix. Participants had a two-room dorm and could therefore fully open a door instead of a window to better modulate room temperature. The other 10 participants opened a window by placing a 10 centimeter long object in the window frame.

From the 19th of October till the 6th of December 2015, measurements were conducted. To assess IEQ, CO_2 levels, temperature, relative humidity (RH) and background noise were measured in two situations: with all doors and windows closed and with an opened door or window. Half of the subjects started with the ‘opened condition’ (higher ventilation rate), the other half started with the ‘closed condition’ (lower ventilation rate). Subjects had been randomly assigned to each group. Each situation was measured for five days, from Sunday evening to Friday morning, with 14 days in between the two different measurement conditions.

Because the subjects had to adapt to the measurement conditions, the data of the first night was omitted for the analysis.

Table 1: Demographics of the subjects

Subject no.	*Gender*	*Age*	*First condition*	*Door or window*	*Building type*	*Date of measurement*	*Flex sensor*
1	Male	23	Open	Window	B	19-25 okt / 9-15 nov	
2	Male	25	Open	Door	A	19-25 okt / 9-15 nov	x
3	Male	25	Open	Door	A	19-25 okt / 9-15 nov	x
4	Male	21	Close	Window	A	19-25 okt / 9-15 nov	
5	Male	22	Close	Window	B	9-15 nov / 30-6 dec	
6	Female	23	Open	Window	B	26-1 nov / 16-22 nov	x
7	Male	22	Open	Window	C	26-1 nov / 16-22 nov	x
8	Female	25	Open	Window	D	26-1 nov / 16-22 nov	
9	Male	21	Close	Window	B	26-1 nov / 16-22 nov	x
10	Female	23	Close	Door	B	26-1 nov / 16-22 nov	x
11	Female	24	Close	Window	A	2-8 nov / 23-29 nov	x
12	Female	22	Open	Door	B	2-8 nov / 23-29 nov	x
13	Male	25	Open	Door	A	2-8 nov / 23-29 nov	x
14	Female	23	Open	Window	E	2-8 nov / 23-29 nov	x
15	Female	23	Close	Door	A	2-8 nov / 23-29 nov	x
16	Male	27	Close	Door	F	16-22 nov / 30-6 dec	
17	Female	23	Open	Window	G	9-15 nov / 30-6 dec	x

The background noise was measured by single point measurement, over ten seconds, with a spectral sound level meter, prior to the experiment. It was measured near the pillow, the window and the door, at the height of the sleeping position. The measurements were performed in the evening, mostly between 18.00 and 22.00. Additionally the background noise was measured for one participant at different times at night. The CO_2, temperature and RH were measured with a sensor with a five-minute interval. The sensors were placed, where possible, about 1.5 meters from the subjects pillow to avoid participants breathing directly upon the sensors. The specifics of the equipment can be seen in the appendix. The ventilation rate (VR) can be obtained from the CO_2 levels and the room volume with Equation 1:

$$VR = \frac{N}{(CO2\_i - CO2\_o)/1000} / V \qquad \textit{Equation 1}$$

N = 15l/h = Production of CO_2 of an average sleeping person, CO_2_i = CO_2 level inside, CO_2_O = 380 ppm = CO_2 level outside (KNMI, 2015), V= room volume (m^3).

Sleep quality

The sleep quality is obtained by qualitative and quantitative measurements as can be seen in Table 2. Questionnaires were used to measure the qualitative sleep quality. The Pittsburgh Sleep Quality Index (PSQI) rates sleep over longer periods of time (Buysse, D. et al, 1988). 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 measuring in the second condition.

The Groningen Sleep Quality Scale (GSQS) is a daily questionnaire with 15 true or false questions. A few questions of the Morning-questionnaire were added to the GSQS questions in one online questionnaire which can be seen in the appendix. These questions of the morning questionnaire were among others ratings of the depth of sleep and restfulness during the night (Mulder H. et al., 1980). This online questionnaire was filled in every morning. The sleep diary was used to indicate when the participants went to sleep and when they woke up. From the sleep diary sleep latency, length of sleep, number of awakenings and sleep efficiency can be derived. The sleep diary was filled in the morning after waking up.

Table 2: Qualitative and quantitative sleep quality measurements with their variables interpretation that can be obtained from them.

Qualitative	**Variables**	**Unit / Range**	**Interpretation**	**Interval**
PSQI	-	0 -21	0 = good, 21 = bad sleep quality	Weekly
GSQS	-	0 - 14	0 = good, 14 = bad sleep quality	Daily
Morning Questionnaire	Rest	1 - 7	1 = not rested, 7 = fully rested	Daily
	Depth	1 - 7	1 = not deep, 7 = very deep	Daily
Sleep diary	Sleep latency	min		Daily
	Length of sleep	hrs		Daily
	No. of awakenings	-		Daily
	Sleep efficiency	0 - 100%		Daily
Quantitative				
Sensewear	Sleep latency	min		1 min.
	Length of sleep	hrs		1 min.
	No. of awakenings	-		1 min.
	Sleep efficiency	0 - 100%		1 min.
Flex sensor	Number of peak/ movement	0 - 300,000 V	Sudden increases = movement	5 min.

During the nights, the participants wore a Sensewear Armband (Figure 1) to measure the sleep quality quantitatively. The Sensewear Armband 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 Armband was worn on the upper right arm only at nights. Additionally a Flex sensor (Figure 2) was used to observe the movement of the subjects during the night. This device was only available for 12 subjects. The Flex sensor measures the resistance at a five-minute interval, which increases when it is bend. The sensor was placed under the pillow of the subject. When a peak appears in the data this was noted as restless behavior. Thereby the amount of times per night the participant showed restless behavior can thus be derived.

Figure 1: SenseWear® MINI Armband (Sensewear)

Figure 2: Flex sensor (Antratek)

Data processing

MATLAB R2014b was used for data collation and preprocessing. IBM SPSS statistics 23 was used to analyze the data. First it was determined if the two conditions are significant different from each other for the IEQ variables. To obtain this information, the normality was tested with a Shapiro-Wilk's test. If the variable was normally distributed, a Paired Sample T-test was executed to test if the two conditions were significantly different. If the variable was not normally distributed, the Wilcoxon Signed-Rank Test was used to determine if the two conditions were significantly different (Baarda and De Goede, 2006). To establish if the experimental design is sufficient, the IEQ variables were tested for a correlation with door versus window, building orientation or location, room characteristics and order of measurement. The Mann-Whitney U Test was used to establish this relation. To determine if the sleep quality showed different results between the two conditions, univariate correlations were attempted to establish between the sleep quality variables and the IEQ variables with the Pearson and Spearman Correlation (Baarda and De Goede, 2006). In addition multivariate correlations tests with a Linear Regression Analysis were the sleep quality variable was implemented as the dependent variable and multiple IEQ variables as independent variables. All the comparisons reported in the results are 2-tailed, with a significant P-value of 0.05.

Results

IEQ

Figure 3A shows the four-day average CO_2 levels per participant in both conditions. The average CO_2 levels at night was 731 ppm in the open condition and 1147 ppm in the closed condition. The CO_2 measurements are not normally distributed, as can be seen in Table 3, but the two conditions had significantly different values ($p < 0.001$). As the ventilation rate is dependent on the CO_2 levels, this variable shows a corresponding significant difference ($p = 0.001$). In the open and closed condition the average ventilation rate is respectively 5.26 ACH and 2.94 ACH. In the four-day average for temperature of both conditions is additionally shown. The average temperature at night was 19.35 °C indoors and 5.76 °C outdoors in the open condition. In the closed condition the temperature was 19.75 °C indoors and 7.05 °C outdoors. The temperature for both conditions is normally distributed and significantly different between the conditions. Finally the average background noise per subject can be seen in Figure 3C. The average sound level of the background noise is 46.07 dB for the open situation and 40.53 dB for the closed situation. Although the background noise in the open condition is normally distributed, in the closed condition it is not. The background noise is significantly different in both situations as can be seen in Table 3 ($p = 0.01$). The relative humidity in the open condition has an average of 56 % (standard deviation 9 %) and in the closed condition 55 % (standard deviation 9 %). In the appendix the measurements of the background noise during the night can be found.

The RH shows no significant difference between the two conditions ($p = 0.871$). The exact data of the IEQ variables per participant can be found in the appendix.

Table 4 shows the P-values for the correlations between the IEQ variables and the different building characteristic, locations and methods. The specifications of building type A can be seen in the appendix. As can be seen in table 2, the temperature has a significant relation with the type of opening variable. The average room temperature with door opened is 18.72 °C and the average with the window opened is 19.95 °C. The CO_2 levels correlate with the room size. A larger room gives a lower CO_2 level: in the bedrooms with a volume larger than 50 m^3, the average CO_2 level was 721 ppm. The average CO_2 in bedrooms smaller than 50 m^3 was 1032 ppm. Additionally, a correlation between the room volume and the background noise can be seen. In the larger bedrooms the average sound level is 47.40 dB, while the rooms smaller than 50 m^3 have an average sound level of 41.59 dB.

Table 3: Statistical analysis of the IEQ variables. A P-value < 0.05 for the normality indicates a deviation form a normal distribution. A P-value < 0.05 from the T-test or Wilcoxon Signed-Rank Test shows a significant difference between the two conditions.

	Normality Open (P-value)	**Normality Close (P-value)**	**Difference (P-value)**
CO2	**0.03**	**>0.001**	**<0.001**
T	0.236	0.092	**0.03**
RH	**0.001**	0.139	0.871
VR	**<0.001**	**<0.001**	**0.001**
Noise	0.185	**0.002**	**0.01**

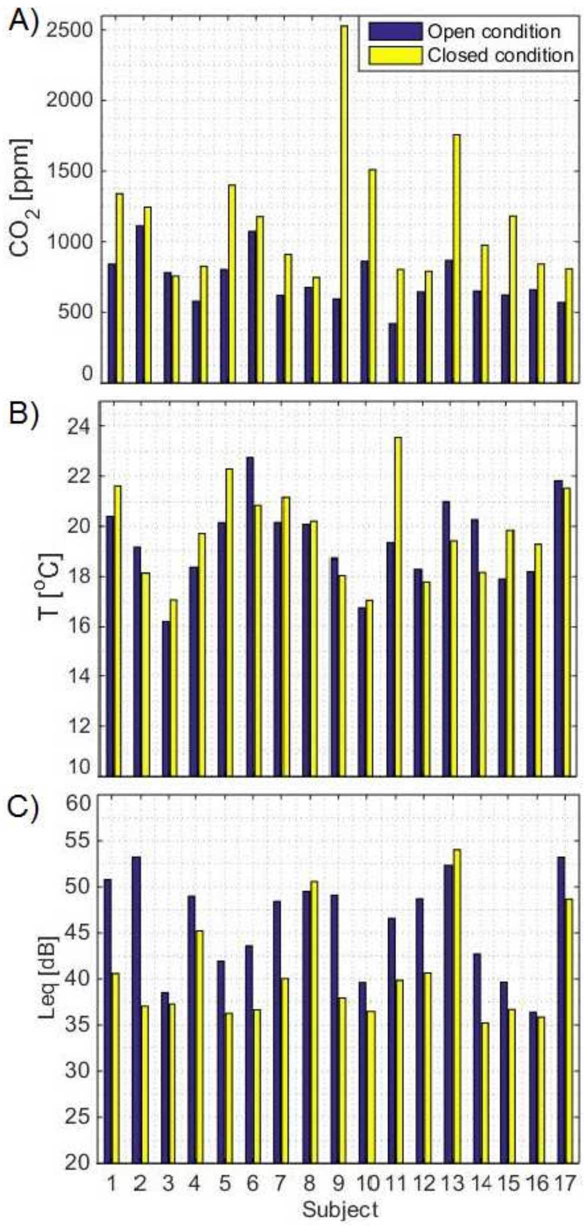

Figure 3: Comparison of the the IEQ in the open condition (blue) and the closed condition (yellow) for all seventeen subjects.

A: CO_2 levels in ppm, B: Temperature in degrees Celsius. C: Background noise level in decibel.

Table 4: Correlations between IEQ variables and different building characteristics, locations or methods. P-values < 0,05, presented in bold, indicate a significant correlation.

	Building type A	Building close to loud street	Large volume >50m^3	Small volume <30m^3	Window or door opened	Situation 1 = open
T	0.217	0.345	0.423	0.27	**0.017**	0.205
CO_2	0.986	0.929	**0.016**	0.642	0.457	0.454
Noise	0.511	0.063	**0.013**	0.809	0.169	0.586
VR	0.074	0.582	0.897	0.079	0.396	0.17

Subjective sleep quality questionnaires

Table 5 shows the results of sleep quality variables that are obtained from the questionnaires in the open and closes conditions. None of the sleep quality variables are normally distributed when tested against the Shapiro-Wilk's test. There is a significant difference for the depth of sleep between the two conditions ($p = 0.001$).

With the Pearson and Spearman correlation, the sleep quality variables are correlated to the IEQ variables. The only significant relation (P-value < 0.05) were between the depth of sleep and the CO_2 ($p = 0.048$) and the temperature ($p = 0.016$) (Table 6). Here, only the significant correlations are given. The depth shows a Pearson correlation coefficient (r) of -0.155 with CO_2, which means a negative correlation is present; higher CO_2 levels show a lower depth of sleep. The corresponding correlation for temperature and depth of sleep is 0.212, which is a positive correlation; when the temperature rises the sleep is likely to be deeper.

The depth of sleep shows the best correlation with temperature and CO_2 combined. The length of sleep did not show a univariate correlation with any of the IEQ variables. However in the table can be seen that the length does show a significant multivariate correlation with the background noise and the CO_2.

Table 5: Mean, minimum, maximum and the standard deviation of sleep quality variables of the questionnaires.

		Mean	Min.	Max.	Std. Deviation
GSQS (score 14-0)	Open	3.18	0.00	13.00	2.69
	Closed	2.96	0.00	11.00	2.31
Sleep quality (score 1-5)	Open	3.44	1.00	5.00	0.88
	Closed	3.38	0.00	5.00	0.92
Depth (score 1-7)	Open	4.21	1.00	7.00	1.59
	Closed	3.38	1.00	5.00	0.92
Rest (score 1-7)	Open	4.71	2.00	7.00	1.22
	Closed	4.60	1.00	7.00	1.28
Latency (min)	Open	22.53	0.00	75.00	16.40
	Closed	22.41	0.00	75.00	16.38
Length (hr.)	Open	8.03	4.50	10.30	0.95
	Closed	7.86	4.80	10.00	0.94
Awakenings (n per night)	Open	0.65	0.00	3.00	0.88
	Closed	0.62	0.00	3.00	0.98
Efficiency (%)	Open	87.70	51.00	97.50	9.38
	Closed	88.39	100.00	62.00	8.17

Table 6: P-values, R^2 and adjusted R^2 from Linear Regression Analysis for multivariate correlations. The analyzed correlations between one sleep quality variable and multiple IEQ variables.

Sleep quality	**IEQ**	**P-value**	**R^2**	**adj. R^2**
Depth	Temperature	0.016	0.036	0.030
	CO_2	0.048	0.024	0.018
	Temp. + CO_2	**0.008**	**0.060**	**0.048**
Length	CO_2	0.894	0.005	-0.001
	Noise	0.116	0.078	0.048
	Noise + CO_2	**0.027**	**0.213**	**0.161**

Correlations sleep quality Sensewear / Flex sensor

Table 7 shows the mean, minimum, maximum and standard deviation for the sleep quality measured by the Sensewear Armband. In addition the amount of times the Flex sensor detected movement is given. None of the sleep quality variables are normally distributed or had significant differences. The results of the flex sensor only contain the data of five of the twelve subjects provided with a flex sensor. As can be seen slightly less movement is detected in the mean open condition. Although, they are similar in the open and closed condition, the mean of all four Sensewear variables seems slightly more positive in the open condition.

Table 8 shows the P-values and R^2 and adjusted R^2 of the Sensewear sleep quality correlating with one or multiple IEQ variables. The length of sleep showed a negative correlation with the ventilation rate (correlation coefficient -0.303). The number of awakenings showed a significant positive correlation with the CO_2 (correlation coefficient 0.191). Additionally the number of awakenings showed a negative correlation with the temperature (P-value 0,039, correlation coefficient -0,160). Although the sleep efficiency showed the most significant correlation with the ventilation rate (correlation coefficient -0,201), it also correlated with the CO_2 (P-value 0.01; correlation coefficient -0.199) and the temperature (P-value 0.012; correlation coefficient 0.194). As the length of sleep correlates most significantly with the ventilation rate, no multivariate show stronger relations. The number of awakenings however, does appear to have a higher significance and dependence with CO_2 and temperature combined (p = 0.001). This is also true for the sleep efficiency (p = 0.005).

Table 7: Mean, minimum, maximum and the standard deviation of sleep quality variables of the Sensewear and Flex sensor.

		Mean	Min.	Max.	Std. Deviation
Latency (min)	Open	22.59	0.00	106.00	17.58
	Closed	23.22	0.00	100.00	19.52
Length (hr.)	Open	8.05	4.00	10.80	1.37
	Closed	7.84	4.80	10.00	1.36
Awakenings (n per night)	Open	2.58	0.00	7.00	1.92
	Closed	2.65	0.00	8.00	2.03
Efficiency (%)	Open	78.17	51.00	96.30	14.25
	Closed	77.96	47.50	96.30	13.66
Flex sensor (n per night)	Open	2.38	0.00	7.00	1.56
	Closed	2.78	0.00	6.00	1.39

Table 8: P-values, R^2 and adjusted R^2 from Linear Regression Analysis for multivariate correlations. The analyzed correlations between one sleep quality variable obtained from the Sensewear data and multiple IEQ variables.

Sleep quality	IEQ	P-value	R2	adj. R2
Length S	VR	**<0.001**	**0.092**	**0.086**
	VR + Noise	0.268	0.81	0.022
Awakenings	CO_2	0.014	0.036	0.030
	Temperature	0.039	0.026	0.020
	CO_2 + Temp	**0.005**	**0.062**	**0.051**
Efficiency	VR	0.009	0.040	0.035
	VR-CO_2	0.029	0.043	0.031
	CO_2 + Temp	**0.001**	**0.078**	**0.067**

Threshold

As mentioned in the previous section, the depth of sleep, number of awakenings and the sleep efficiency shows a relation with the CO_2. An attempt was made to obtain a threshold for a CO_2 level for which a change in the sleep quality appears. The Mann Whitney U test was carried out. For different levels of CO_2 the mean rank of the sleep quality variables above and below this level is compared, which is displayed in Figure 6, Figure 5 and Figure 4.

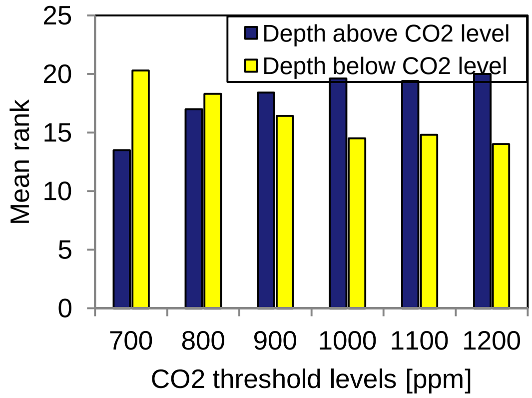

Figure 4: Mean rank of depth of sleep from Mann Whitney U test above and below different levels of CO_2.

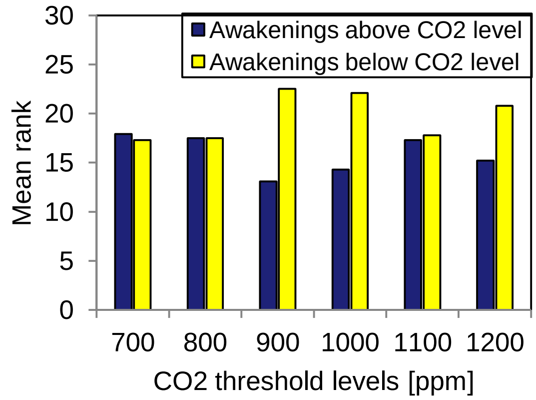

Figure 5: Mean rank of number of awakenings from Mann Whitney U test above and below different levels of CO_2.

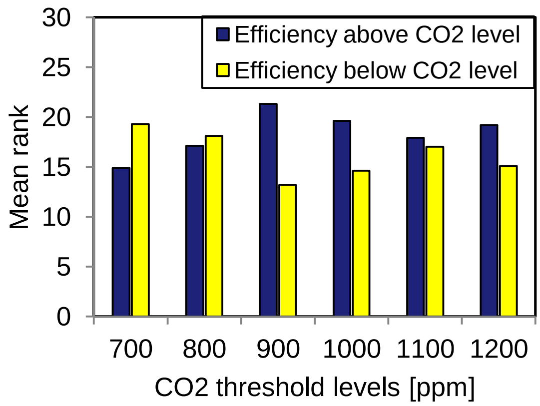

Figure 6: Mean rank of sleep efficiency from Mann Whitney U test above and below different levels of CO_2.

Discussion

The aim of this study is to obtain the sleep quality in two different conditions, to find a relation between sleep quality and indoor air quality. The two conditions should therefore be significant different in CO_2 levels. Furthermore it was aimed to determine whether there is a relation between sleep quality and CO_2 levels in the bedrooms of healthy adults. If a correlation is found, a threshold for a CO_2 concentration from which sleep quality starts getting impaired is tried to be found. Finally different measurement methods are examined to obtain how sleep quality can best be measured.

IEQ variables

The CO_2 levels in the room of subject three showed little to no difference between the two conditions. As the subject participated in this study in the same time and building as several other subjects, this is most likely due to a human error or instrument error. A significant difference of CO_2 means that the experimental design is successfully carried out as intended. The higher ventilation rate, calculated with the CO_2 concentrations, can reduce the pollutant concentration in the room. The significant difference between the two conditions for this variable can therefore additionally be seen as a desired outcome of the experimental design. The temperature and background noise show a significant difference as well. This indicates that any difference in sleep quality could also be a derivative of these other variables. For an optimal experimental design, these IEQ parameters should be controlled in the sleep environment. As can be seen in Table 4 the temperature shows a correlation with type of opening. The average temperature in the rooms with windows opened is higher, which could be explained by the temperature difference outside, which was on average 1.3 ^oC lower in the window open instead of the door. Additionally the participants could set the desired indoor temperature. Therefore the difference per participant between the opened and closed conditions could give a better indication of which setup, door or window, shows the least difference in temperature. The temperature difference is larger for the window variant than for the door variant. Similarly, the back ground noise difference between the two conditions is larger for the window variant than for the door variant, this can also be seen in the appendix were the measurements during the night are given. To control the environmental parameters opening a door is therefore favorable to decrease the CO_2 levels in the sleep environment. By opening a door, the effective room size enlarges, which, as seen in Table 4, also correlates with the CO_2 levels. However, since CO_2 seems to decrease in a volume larger than 50 m^3, for similar future research, smaller rooms are suggested.

Correlation between sleep quality from questionnaire and IEQ

Although there is no high dependency of depth of sleep on temperature and CO_2, as can be seen in Table 6, the results show a significant improvement in the depth of sleep with lower CO_2 levels and higher temperatures. This finding corresponds with the data of Laverge (2011) where lighter sleep was reported under low ventilation rates. The length of sleep significantly increases with a higher background noise and a higher CO_2 level, however this is a difficult variable to correlate to the environmental parameters since length of sleep is highly dependent on the life style and preferences of the subject. Although there is a significant correlation noted, the incensement of sleep quantity does not necessarily indicate an increase in sleep quality (Pilcher, 1997). Strøm-Tejsen (2014a) noted a (non-significant) tendency of the subjects reporting to sleep better (GSQS) with the window opened and Laverge (2011) noted an opposite trend. Both conducted the measurements with similar methods as this study. However, no difference was found for the GSQS in this study. Cremers (2015) showed a correlation between the CO2 levels and the restlessness. However, no significant correlations can be found for the restlessness during sleep. The result from Cremers was based upon caretaker observations. The subjects in this study rated subjectively their restlessness the following morning, which might be different than their actual behavior during the night, causing the difference in findings. Additionally the subject studied by Cremers suffered of dementia, which could cause the differences in outcome.

Correlation between sleep quality from Sensewear and IEQ

The results from the Sensewear Armband show a significant increase in length of sleep with lower ventilation rates. As mentioned above, this variable is arguable as an indicator of sleep quality, however it does show that the sleep quantity can be influenced by the IEQ. The number of awakenings noted by the Sensewear Armband seems to decrease when the CO_2 levels are lower and the temperature is higher. An increment in awakenings leads to a decrease in sleep efficiency, since less time is spent sleeping. This is shown in the results as the sleep efficiency significantly increases with a lower CO_2 levels and higher temperatures. A similar tendency was noted by Strøm-Tejsen (2014a) where the efficiency (non-significantly) improved in the open window condition. The sleep latency does not show a tendency of improvement for any of the environmental parameters, whereas Strøm-Tejsen (2014a) did observe a decrease in the sleep latency in the open window condition.

Threshold

For the three sleep quality variables that correlated with CO_2, a threshold at which the sleep quality deteriorates has been tried to be confirmed. In a visual representation of the correlations, as can be seen in the appendix, no threshold could be established. The depth of sleep and sleep efficiency in Figure 6 and Figure 4 can be seen that at the levels of 700 ppm and 800 ppm the values below these levels are higher. For the number of awakenings at a threshold of 700 ppm the number of awakenings below this level is lower. At a level of 800 ppm the number of awakenings above and below this level is the same. This supports the threshold of 800 ppm noted by Cremers (2015). This finding, however not significant, is intriguing and would need to be further examined in future research, with larger groups of participants.

Sleep quality measurements

Sensewear Armband and questionnaire

In this research multiple methods are used to measure the sleep quality. Similar results can be obtained from the questionnaire, as from the Sensewear Armband. Although the subjective sleep quality do not give the exact same data as the objective sleep quality when comparing means, the two methods show a highly significant relation for the sleep latency, length of sleep and number of awakenings, and a significant, but less strong correlation with sleep efficiency. This suggests that the data from Sensewear could be supported by subjective sleep quality data. This correlation despite the differences between the exact data, could be explained by the subjects not remembering the exact sleep quality at night but still noticing the differences between the different nights.

Flex sensor

As mentioned before, the restlessness might be difficult to be indicated by participant subjective rating. The Flex sensor could indicate the amount of times movement and restless behavior was shown in an objective manner. However, of the 12 subjects that where provided with a Flex sensor, the data of seven subjects was omitted. For these subjects the sensor was measuring the maximum resistance during the whole experiment, probably because of a displaced sensor. Because of this lack of data, no statistical analysis was performed. The data did however show resemblance to the metabolism, measured by the Sensewear Armband, and could probably show relevant results when carried out successfully.

Experimental design

This study gives an impression of the effect of CO_2 on sleep quality and sustains early executed work. When further research is conducted, a larger amount of participants (31 subjects) could be required to increase the significance of the results, as can be seen in the appendix. Furthermore the participants were all students of the age 20 to 30. Some students showed an irregular lifestyle and sleeping pattern, which could have reduced the likelihood of obtaining relevant results. Selecting subjects with a more regular lifestyle could increase the probability of significant results. The subjects were additionally not unaware to the intervention, which could have influenced their reactions to the questionnaires. For future research, fully controlled mechanical ventilation is suggested to control IAQ in the sleep environment and to keep the subjects blinded to the intervention. The choice for presenting the questionnaire online can also be questioned since occasionally the subjects forgot to fill it in, while the sleep diary on paper was filled in every day just after waking up. Four days were taken into account for the data analysis. However, many variations between the four days could be seen, possible among other due to the irregular lifestyles of the students. For less variation, a longer measurement period could be required.

Conclusion

In this paper the influence of the indoor air quality, indicated by CO_2 levels, on sleep quality was examined. The measurement results showed an average of 729 ppm when the window or door was open and an average of 1135 ppm when all windows and doors were closed. Results from the questionnaire showed a relation between CO_2 levels and temperature and the depth of sleep, where lower CO_2 levels and higher temperature correlate to deeper sleep. Additionally quantitative measurements were used to measure the sleep quality variables sleep latency, length of sleep, number of awakenings and sleep efficiency. From this device, the data obtained suggests that the number of awakenings decrease with lower CO_2 levels and higher temperatures. The sleep efficiency increases in the same conditions. Furthermore, at a CO_2 level of 800 ppm the depth of sleep and sleep efficiency seem to decrease, and the number of awakenings seems to increase. Although the questionnaires did not seem to show the same data as the Sensewear data, the results did show highly significant correlation between the number of awakenings, sleep latency and the sleep efficiency.

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Figures

Figure 1: SenseWear® MINI Armband , n.d. photograph, viewed 20 april 2016, http://sensewear.nl/

Figure 2: Flex sensor (Antratek, Flexsensor, n.d. photograph, viewed 20 april 2016, <https://www.antratek.nl/flex-sensor-4-5>.

3 Appendix

Index

1. Introduction

2. Methodology

Supporting data for results and discussion

Introduction

Table 9 shows the result of previous conducted studies about sleep quality and indoor air quality.

Table 9: Effect of high or low ventilation rate on sleep for four articles. The positive effects of high or low ventilation are given

	Improved sleep quality of open situation	*Decreased sleep quality of open situation*
Laverge et al (2011) no. subjects: 8 days measured: 4	- Shorter awakenings - Deeper sleep - Better rested/alert when waking	- Sleep efficiency slightly decreased - More awakenings
Laverge et al (2014) no. subjects: 8 days measured: 4	- Deeper sleep - Higher sleep quality - Shorter sleep latency	- Shorter sleep - More awakenings - Sleep efficiency lower (1)
Strøm-Tejsen et al. (2014a) no. subjects: 14 days measured: 4	- Shorter sleep latency(1) - Higher sleep efficiency(1) - Fresher air - Easier to fall asleep	- Dry air
Strøm-Tejsen et al. (2014b) no. subjects: 14 days measured: 4	- Higher sleep efficiency(1) - Fresher air - Better mental state - More rested	- Dry air

(1) Objective sleep quality results by measured by actigraphy technique

Method

Experimental design

In Table 10 the different buildings, and their building characteristics, can be seen.

Table 10: Building characteristics

Building letter	Building year	Construction	Room size	Orientation window	Ventilation
A	1959	Concrete, Apartments	Surface: 9m^2 (subject 4: 22m^2) Height: 2,7m	East or west	Mechanical supply
B	1995-2000	Concrete, brick, Apartments	Surface: 18m^2 Height: 2,4m (subject 12: 3,1m)	East or west	Mechanical supply
C	2004	Concrete, Apartments	Surface: 20m^2 Height: 2,5m	East	Mechanical supply
D	1983	Brick, terraced house	Surface: 24m^2 Height: 2,4m	South	Mechanical supply
E	1930	Concrete, brick, Apartments	Surface 15,8m^2 Height: 3m	East	Mechanical supply
F	2014	Concrete, Apartments	Surface: 15m^2 Height: 3m	West	Mechanical supply and exhaust
G	1979	Concrete, Apartments	Surface: 19,3m^2 Height: 2,9m	East	Mechanical supply

Table 11 shows information about the subjects, when the measurements took place for which subject and which equipment is used for this subject.

Table 11: Subject information

Subject no.	*Gender*	*Age*	*First condition*	*Door or window*	*Building type*	*Date of measurement*	*Logger*	*Flex sensor*	*Sense -wear*
1	Male	23	Open	Window	B	19-25 okt 9-15 nov	H0400	No	k33
2	Male	25	Open	Door	A	19-25 okt 9-15 nov	H0800	Yes	34
3	Male	25	Open	Door	A	19-25 okt 9-15 nov	H1000	Yes	8
4	Male	21	Close	Window	A	19-25 okt 9-15 nov	H0700	No	5
5	Male	22	Close	Window	B	9-15 nov 30-6 dec	H0400	No	k88
6	Female	23	Open	Window	B	26-1 nov 16-22 nov	H0400	Yes	k33
7	Male	22	Open	Window	C	26-1 nov 16-22 nov	H0900	Yes	8
8	Female	25	Open	Window	D	26-1 nov 16-22 nov	H0800	No	9
9	Male	21	Close	Window	B	26-1 nov 16-22 nov	H1000	Yes	32
10	Female	23	Close	Door	B	26-1 nov 16-22 nov	H0700	Yes	34
11	Female	24	Close	Window	A	2-8 nov 23-29 nov	H1000	Yes	k88
12	Female	22	Open	Door	B	2-8 nov 23-29 nov	H0800	Yes	k36
13	Male	25	Open	Door	A	2-8 nov 23-29 nov	H0900	Yes	k13
14	Female	23	Open	Window	E	2-8 nov 23-29 nov	H0700	Yes	k87
15	Female	23	Close	Door	A	2-8 nov 23-29 nov	H0600	Yes	34
16	Male	27	Close	Door	F	16-22 nov 30-6 dec	H0400	No	K13
17	Female	23	Open	Window	G	9-15 nov 30-6 dec	H0900	Yes	K36

Sample size

The required amount of subjects can be calculated with Equation 1, (Montgomery D.C., Runger G.C., 2011). To calculate the sample size the CO_2 levels are used. With a significance level of 0.90, $Z_{\alpha/2}$ is 1.65 and with a power of 0.05, Z_β is 1.28 (Montgomery D.C., Runger G.C., 2011). The variance (σ^2) in the open window situation, calculated with SPSS, is 352879,50. The effect size (d^2) can be calculated with Equation 3 (µ1=1147ppm, µ2=731ppm) and is in this case 173129.40.

Equation 1: Sample size calculation: n= sample size, a= significance level = 0,90, 1-b= Power=0,05, σ = standard deviation, d= effect size

$$n = \frac{2 * (Z\alpha/2 + Z\beta)^2 * \sigma^2}{d^2}$$

Equation 2: effectsize: µ1= average condition 1, µ2= average condition 2

$$d^2 = \mu 1 - \mu 2$$

The sample size that would be needed for a reliable research is therefore 31 subjects. For this study 17 subjects were selected, because only six subjects could participate per week, because of the amount of available equipment. Furthermore only six weeks of measurement were available because of lack of time and interference with Christmas holiday. One subject was omitted form the study because of an power outlet.

Specifications equipment

Table 12: Specifications of equipment used to measure the IEQ and the sleep quality.

	TU/e ID	Output	Conversion (x=sensor output)	Range	Interval
GW47 CO_2, RH and temp transmitter	18718, 18733, 19158, 18728, 18719, 19156, 18727, 18734, 18724, 18717	0-5 [V]	CO_2 = x*1000(1) RV = x*20 T = 8*x+5(1)	0-5000 [ppm] 0-100 [%] 5-45 [°C]	5 min
Flex sensor	-	0-300.000 [V]	-	-	5 min
Grant squirrel data logger	H0400, H0600, H0700, H0800, H0900, H1000	-	-	-	-
RION, NL-32, Spectral sound level meter	-	L_A [dB]	-	0-100dB (20 Hz-12,5 kHz)	10 sec (no interv.)
Sensewear Armband	-	MET, Sleep classification			1 min

(1) Conversion is deviating from the formula per sensor

Sleep quality questionnaires

In Figure 7 the sleep diary can be seen, in Dutch. In this timeline the subjects could indicate in the following morning, when they went to bed, when they fell asleep and when they woke up. Additionally an comments section was given for further information.

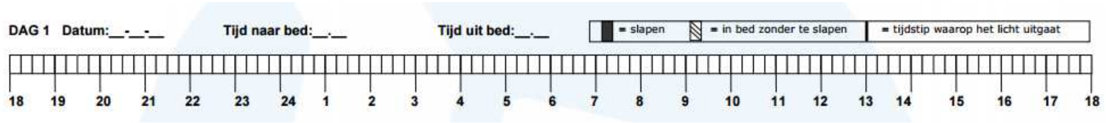


Figure 7: Sleep diary.

The following pages shows the Pittsburgh Sleep Quality Index and the morning questionnaire. Both are shown in Dutch as all participants were of Dutch nationality.

Pittsburgh sleep quality index **Deelnemers nummer:**

1	Hoe laat ging u de afgelopen twee weken gewoonlijk naar bed?	Uur	Minuut
2	Hoe lang heeft het gemiddeld in de afgelopen twee weken geduurd voordat u inslaap viel gemiddeld?	Uur	Minuut
3	Hoe laat stond u gemiddeld op in de afgelopen twee weken?	Uur	Minuut
4	Hoeveel uur heeft u werkelijk geslapen per nacht in de afgelopen twee weken?	Uur	Minuut

Voor elke volgende vraag zet een kruisje bij het beste antwoord. Antwoordt alstublieft alle vragen.

5	In de afgelopen twee weken, hoe vaak had u problemen met slapen omdat je…	*Niet in de afgelopen twee weken*	*Minder dan een keer per week*	*Een of twee keer per week*	*Drie of meer keer per week*
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 de wc te gaan				
d	Niet comfortabel kon ademen				
e	Moest hoesten of hard snurken				
f	Het te koud had				
g	Het te warm had				
h	Nachtmerries/ nare dromen had				
i	Pijn had				
j	Andere redenen, (graag omschrijven en aangeven hoe vaak)				

Zet een kruis bij het correcte antwoord.

6	Hoe goed beoordeel je je slaap kwaliteit van de afgelopen twee weken	*Erg goed*	*Redelijk goed*	*Redelijk slecht*	*Erg slecht*
7	Hoe vaak heeft u medicijnen gebruik om in slaap te komen in de afgelopen twee weken?	*Niet in de afgelopen twee weken*	*Minder dan een keer per week*	*Een of twee keer per week*	*Drie of meer keer per week*
8	Hoe vaak heeft u, in de afgelopen twee weken, moeite om wakker te blijven wanneer u aan het autorijden of eten was of wanneeru deelnam in sociale activiteiten?	*Niet in de afgelopen twee weken*	*Minder dan een keer per week*	*Een of twee keer per week*	*Drie of meer keer per week*
9	In de afgelopen twee weken, hoe veel moeite heeft u moeten doen om genoeg enthousiasme op te brengen om dingen gedaan te krijgen?	Geen moeite	Alleen een klein beetje moeite	Enigszins moeite	Erg veel moeite
10	Heeft u een bed partner of kamergenoot?	*Ja*	*Nee*		
	Als u een bed partner of kamergenoot heeft, vraag hem/haar of jij in de afgelopen weken..	*Niet in de afgelopen twee weken*	*Minder dan een keer per week*	*Een of twee keer per week*	*Drie of meer keer per week*

Ochtend vragenlijst

Nederlandse versie

1. **DeelnemersNummer**

____

2. **Hoe beoordeel je je slaapkwaliteit van de afgelopen nacht?**
   Denk hierbij aan inslaaptijd, aantal ontwakeningen snachts, hoe energiek je je nu voelt, enz.
   Markeer slechts één ovaal.

	1	2	3	4	5	
Zeer slecht	◯	◯	◯	◯	◯	Zeer goed

3. **Heb je lichamelijke klachten deze ochtend? (Zo ja, omschrijf)**

____

4. **Geef een cijfer aan je slaap kwaliteit van vannacht door een nummer tussen 1 tot 7 te kiezen. Mijn slaap vannacht was...**
   Markeer slechts één ovaal per rij.

	1	2	3	4	5	6	7
1= Erg diep, 7= Erg licht	◯	◯	◯	◯	◯	◯	◯
1= Erg kort, 7= Erg lang	◯	◯	◯	◯	◯	◯	◯
1= Onderbroken, 7= Onafgebroken	◯	◯	◯	◯	◯	◯	◯
1= Droomloos, 7= Met veel dromen	◯	◯	◯	◯	◯	◯	◯
1= Erg rusteloos, 7= Zeer rustgevend	◯	◯	◯	◯	◯	◯	◯

5. **Waar werd je wakker van vanochtend?**
   Markeer slechts één ovaal.
   - ◯ Een gezette alarmklok
   - ◯ Geluid
   - ◯ Ongemak
   - ◯ Spontaan
   - ◯ Anders: ______________________

6. **1. Ik heb diep geslapen vannacht**
   Markeer slechts één ovaal.
   - ◯ Ja
   - ◯ Nee

7. **2. Ik heb het gevoel dat ik slecht heb geslapen vannacht**
   Markeer slechts één ovaal.
   - ◯ Ja
   - ◯ Nee

8. **3. Het duurde meer dan een half uur voordat ik in slaap viel**
   Markeer slechts één ovaal.
   - ◯ Ja
   - ◯ Nee

9. **4. Ik ben meerdere keren wakker geworden vannacht**
   Markeer slechts één ovaal.
   - ◯ Ja
   - ◯ Nee

10. **5. Ik voelde me moe nadat ik wakker werd vannacht**
    Markeer slechts één ovaal.
    - ◯ Ja
    - ◯ Nee

11. **6. Ik heb het gevoel dat ik niet genoeg slaap heb gekregen vannacht**
    Markeer slechts één ovaal.
    - ◯ Ja
    - ◯ Nee

12. **7. Ik ben midden in de nacht opgestaan**
    Markeer slechts één ovaal.
    - ◯ Ja
    - ◯ Nee

13. **8. Ik voelde me uitgerust nadat ik opstond deze ochtend**
    Markeer slechts één ovaal.
    - ◯ Ja
    - ◯ Nee

14. **9. Ik heb het gevoel dat ik maar een paar uur heb geslapen vannacht**
    Markeer slechts één ovaal.
    - ◯ Ja
    - ◯ Nee

15. **10. Ik voel dat ik goed heb geslapen vannacht**
    Markeer slechts één ovaal.
    - ◯ Ja
    - ◯ Nee

16. **11. Ik heb geen oog dicht gedaan vannacht**
    Markeer slechts één ovaal.
    - ◯ Ja
    - ◯ Nee

17. **12. Ik had geen problemen om in slaap te vallen afgelopen nacht**
    Markeer slechts één ovaal.
    - ◯ Waar
    - ◯ Niet waar

18. **13. Nadat ik snachts wakker werd had ik moeite om in slaap te vallen**
    Markeer slechts één ovaal.
    - ◯ Ja
    - ◯ Nee

19. **14. Ik heb de hele nacht liggen te draaien in bed**
    Markeer slechts één ovaal.
    - ◯ Ja
    - ◯ Nee

20. **15. Ik heb minder dan 5 uur geslapen vannacht**
    Markeer slechts één ovaal.
    - ◯ Ja
    - ◯ Nee

Leaving the first day out of data analysis

In Table 13 the mean, standard deviation, minimum and maximum of the average weekly sleep quality of the subjects is given. Once for a five day average and once with the first measurement day left out, to see if the first day affects the sleep quality of the subjects because they haven't accustomed to the conditions yet. As can be seen the data seems to be similar although for all four sleep quality variables. The mean of the sleep latency, number of awakenings and length of sleep seem slightly better.

In Table 14 the 5-day measurement and the 4-day measurement with the first measurement day left out are compared for significant difference with the Wilcoxon signed rank test. As can be seen all four sleep quality variables are not significant different and have a significant correlation. These results indicate that the first day does not seem to be deviating much, which could indicates that the subjects did not experience much distress from the change in environment or the bracelet. However for this study the first day is still left out to exclude a possible unseen effect.

Table 13: The data of the sleep latency, number of awakenings, length of sleep and the sleep efficiency, obtained from the Sensewear Armband can be seen. The mean, standard deviation, minimum and maximum of these sleep quality variables can be seen for five days and for four days where the first day is left out.

		Mean	Std. Deviation	Minimum	Maximum
Latency	5-days	23,15	9,32	5,80	43,00
	4-days	22,84	9,35	5,75	40,75
Awakenings	5-days	2,65	1,50	0,20	6,60
	4-days	2,59	1,53	0,25	7,00
Length	5-days	8,04	0,73	6,25	9,35
	4-days	7,99	0,80	5,70	9,27
Efficiency	5-days	78,96	9,32	55,40	90,78
	4-days	78,38	9,83	56,50	92,00

Table 14: The sleep latency, number of awakenings, length of sleep and the sleep efficiency, obtained from the Sensewear Armband from five day weekly average compared to the four day weekly average. The P-values for significant difference with the Wilcoxon signed rank test and the Pearson correlation.

	Wilcoxon signed rank test P-value	Pearson P-value
Latency	0,642	<0,001
Length	0,279	<0,001
Awakenings	0,585	<0,001
Efficiency	0,959	<0,001

Additional data supporting for the results and discussion

IEQ variables

Table 15: IEQ variables of per participant in the open and closed conditions.

Subject no.	CO2		Temperature		Noise		VR	
	Open	*Close*	*Open*	*Close*	*Open*	*Close*	*Open*	*Close*
1	852	1352,4	20,4	21,7	50,8	40,6	0,86	0,52
2	1127,3	1275,3	19,1	18,1	53,2	37	0,95	0,29
3	789,7	764,1	16	17,5	38,5	37,3	1,47	0,03
4	580,2	835,7	18,5	19,4	49	45,2	1,39	0,8
5	769	1399,2	19,9	22,3	41,9	36,3	0,86	0,61
6	1057,7	1208,9	22,6	20,7	43,6	36,6	0,55	0,2
7	629,6	902,6	20,1	21,1	48,4	40	1,39	0,77
8	668,5	759,4	19,9	20,2	49,5	50,6	1,09	0,43
9	582,6	2363,2	18,7	18	49,1	37,9	2,05	1,91
10	861,5	1434,5	16,8	17	39,6	36,5	0,74	0,49
11	419,3	804,5	19,2	23,5	46,6	39,9	24,14	22,74
12	673	795,2	17,8	17,8	48,7	40,7	0,95	0,39
13	888,8	1772,8	20,7	19,4	52,3	54	1,45	1,07
14	665,6	1018,4	20,3	18,1	42,7	35,2	1,3	0,76
15	636,7	1215,1	17,6	19,8	39,6	36,7	2,38	1,79
16	653,6	848,5	18,2	19,2	36,4	35,9	1,25	0,56
17	570,4	797,8	22	21,3	53,2	48,7	1,78	1,11

In Table 15 the weekly average IEQ variables per participant can be seen for both situations. Figure 8 shows the background noise during the night. As can be seen the window situation shows a clear increase in background noise. The door opened and the door closed give often similar results.

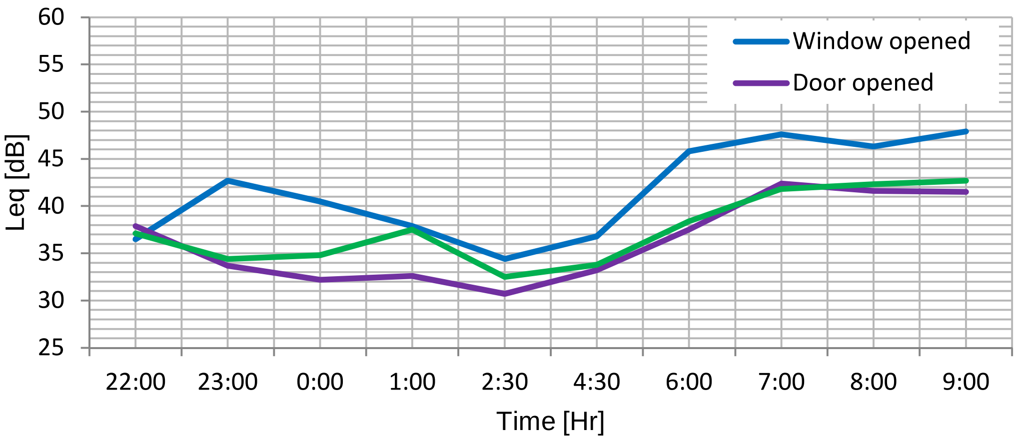


Figure 8: The back ground level measured during the night. The blue line indicated the measurements took place when a window was opened, the purple line indicates the situation when a door was opened and the green indicates a situation where both door and windows were closed.

Correlations IEQ and sleep quality

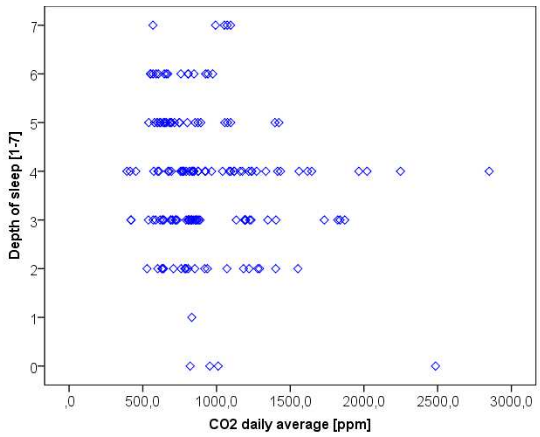
The different sleep quality variables that are derived from the questionnaires and Sensewear Armband can be seen in Table 16. With the Pearson and Spearman correlation, the sleep quality variables are correlated to the IEQ variables. The P-value smaller than 0,05 shows a significant correlation, in the table indicated in bold numbers. The corresponding correlation coefficients are given as well.

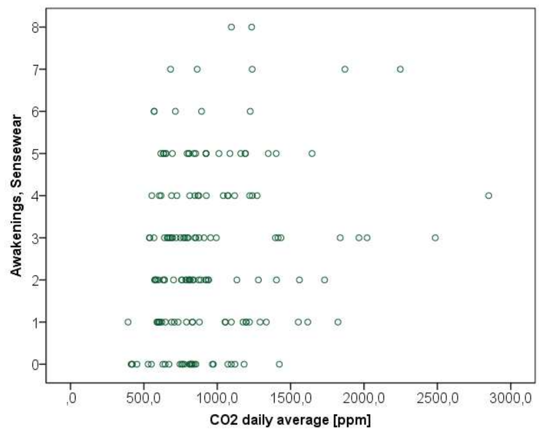
Table 16: the correlation coefficient and the P-value of the univariate correlations between the IEQ and sleep quality (both questionnaires and Sensewear).

		Pearson				**Spearman**			
		CO2	**T**	**Noise**	**VR**	**CO2**	**T**	**Noise**	**VR**
GSQS	Cor. Coeff.	-0,063	0,061	0,19	-0,099	-0,039	0,031	0,143	-0,022
	P-value	0,428	0,441	0,307	0,212	0,622	0,692	0,442	0,781
Sleep quality	Cor. Coeff.	-0,08	0,06	-0,301	-0,039	-0,035	0,102	-0,29	-0,079
	P-value	0,314	0,447	0,1	0,626	0,659	0,198	0,114	0,321
Depth	Cor. Coeff.	**-0,155**	**0,188**	-0,145	-0,006	-0,142	**0,212**	-0,189	0,113
	P-value	**0,048**	**0,016**	0,435	0,937	0,071	**0,007**	0,308	0,152
Rest	Cor. Coeff.	-0,049	0,037	-0,333	-0,079	0,01	0,09	-0,324	-0,084
	P-value	0,539	0,638	0,067	0,318	0,902	0,255	0,075	0,288
Latency Questionn**.**	Cor. Coeff.	0,006	-0,113	0,101	-0,12	0,058	-0,056	0,093	-0,006
	P-value	0,935	0,148	0,577	0,123	0,454	0,47	0,605	0,935
Length Questionn**.**	Cor. Coeff.	0,07	-0,019	-0,279	-0,037	0,027	-0,015	-0,304	-0,032
	P-value	0,372	0,807	0,116	0,635	0,732	0,851	0,085	0,68
Awakenings Questionn**.**	Cor. Coeff.	0,063	-0,002	0,141	-0,08	0,108	0,003	0,206	-0,036
	P-value	0,422	0,984	0,433	0,307	0,167	0,969	0,251	0,649
Efficiency Questionn**.**	Cor. Coeff.	-0,02	-0,062	-0,235	0,039	-0,068	-0,029	-0,151	0,077
	P-value	0,801	0,425	0,187	0,615	0,382	0,711	0,402	0,321
Latency Sensewear	Cor. Coeff.	0,041	-0,061	0,04	-0,089	0,048	0,027	-0,093	0,017
	P-value	0,603	0,435	0,824	0,248	0,537	0,73	0,6	0,821
Length Sensewear	Cor. Coeff.	0,08	-0,031	-0,233	**-0,303**	0,051	-0,041	-0,233	-0,053
	P-value	0,304	0,689	0,184	**<0.001**	0,515	0,6	0,184	0,492
Awakenings Sensewear	Cor. Coeff.	**0,191**	**-0,16**	0,306	-0,065	**0,172**	-0,132	0,273	-0,06
	P-value	**0,014**	**0,039**	0,078	0,396	**0,026**	0,089	0,118	0,439
Efficiency Sensewear	Cor. Coeff.	**-0,199**	**0,194**	-0,199	**-0,201**	**-0,186**	0,103	-0,182	0,07
	P-value	**0,01**	**0,012**	0,26	**0,009**	**0,017**	0,188	0,304	0,363

Threshold

Figure 9 visually shows the correlations between CO_2 and Depth of sleep, Number of awakenings and Sleep efficiency. From these graphs the threshold was attempted to be obtained. As can be seen in the figures, no clear visual correlations can be seen.





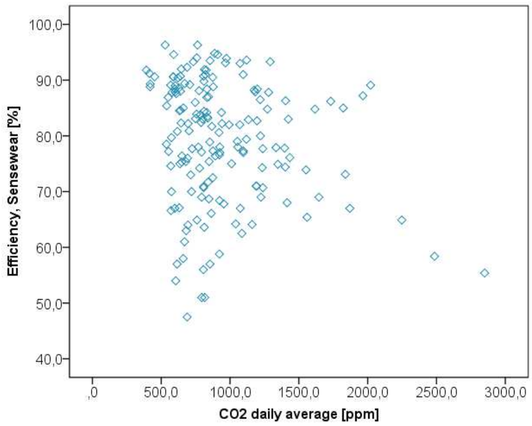


Figure 9; Upper Left: correlation between CO_2 levels and depth of sleep.

Upper right: correlation between number of awakenings and the CO_2.

Lower: correlation between efficiency and CO_2 levels.

Correlation sleep quality questionnaires and Sensewear

Table 17 shows the average of the latency, length of sleep, number of awakenings and sleep efficiency for both the questionnaire and the Sensewear results. As can be seen that although the length of sleep and latency do show similarities in the mean, the number of awakenings and the sleep efficiency. Therefore the two sleep quality measurement methods are correlated with the Pearson and Spearman correlations, to obtain information about the similarities. As can be seen all sleep quality variables show a significant P-value. However the correlation coefficients of the number of awakenings and sleep efficiency are rather low.

Table 17: Correlations between the sleep quality variables obtained from the questionnaires and Sensewear Armband.

		Pearson	Spearman	Mean	
Latency	Corr. Coeff.	0,445	0,285	22,289	Questionnaire
	P-value	**<0,001**	**<0,001**	22,906	Sensewear
Length	Corr. Coeff.	0,866	0,866	7,961	Questionnaire
	P-value	**<0,001**	**<0,001**	7,945	Sensewear
Awakenings	Corr. Coeff.	0,279	0,289	0,62	Questionnaire
	P-value	**<0,001**	**<0,001**	2,61	Sensewear
Efficiency	Corr. Coeff.	0,154	0,24	88,094	Questionnaire
	P-value	**0,047**	**0,002**	78,069	Sensewear

Metabolism

The article mentioned the Sensewear Armband measuring the metabolism. In this study an attempt was made to find a direct correlation between the CO_2 levels and the metabolism. The metabolism is measured on an interval of one minute, which was converted to a ten minute interval for a direct correlation. With a Pearson correlation the open and closed conditions were examined for a correlation as can be seen in Table 18. Only the results for the first three subjects are given to give an impression of the results. As can be seen the metabolism of subject one and three shows a significant correlation for one situation. Additionally subject two and subject three show a positive correlation in the open condition but a negative correlation for the closed condition. Because of the diversity in results this variable is not further examined. However there seems to be a certain correlation which can be interesting for future research.

Table 18: Correlation between metabolism and CO_2 for both the open condition and the closed condition obtained from the Pearson correlation.

		Open condition	Closed condition
Subject 1	Correlation coefficient	0,219	0,104
	P-value	**>0,001**	0,123
Subject 2	correlation coefficient	0,172	-0,255
	P-value	**0,006**	**>0,001**
Subject 3	correlation coefficient	0,12	-0,226
	P-value	0,101	**0,002**