Window/door opening-mediated bedroom ventilation and its impact on sleep quality of healthy, young adults

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The influence of carbon dioxide levels on sleep of healthy Dutch adults

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Abstract

This work examines the effect of bedroom indoor air quality, as indicated by carbon dioxide (CO₂) levels, upon sleep parameters. Data of 17 healthy volunteers was used in this study. In their bedrooms, the CO₂ level, temperature, background noise, and relative humidity were measured over 5 days, for two cases each: 1) open window or door, and 2) closed window and door. The participants filled a questionnaire and a sleep diary every morning to give a subjective measure of sleep quality. Actigraphy was employed to objectively monitor the participants during sleep. Additionally, a flex sensor, placed under pillows of participants, was used to detect movement during sleep. Average CO₂ level for the open window/door condition was 731 ppm (sd = 187 ppm) while it was 1147 ppm (sd = 431 ppm) for closed conditions. Depth of sleep, measured by the questionnaire, was significantly different between the two conditions ($p = 0.002$). Lower CO₂ levels and warmer temperatures (over the entire range of 15 to 25 °C) correlated to a deeper sleep

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($R^2 = 0.06$, $p = 0.008$). Actigraphy data showed that with lower CO_2 levels and warmer conditions, number of awakenings tended to decrease while sleep efficiency improved. Results also showed a significant correlation ($p < 0.05$, $r = 0.15\text{--}0.87$) between objective actigraphy data and subjective responses to questionnaires. Analysis also suggests a ‘threshold’ value of CO_2 for bedrooms, close to 1150 ppm, beyond which sleep of healthy young adults may start getting compromised.

Keywords: sleep quality, bedroom, indoor air quality, carbon dioxide, field study, actigraphy

1. Introduction

About a third of the life of an average person is spent asleep [1, 2]. The course of sleep has been differentiated into several stages, of which, the slow-wave sleep (SWS) and rapid eye movement (REM) stages are required for a good sleep and are respectively necessary for physical and mentally recovery [1]. Poor sleep quality can have direct and indirect economic implications as well, by affecting productivity and workplace safety [3]. Previous reviews have unequivocally asserted that the indoor environment quality (IEQ) elements like temperature, lighting, background noise etc., impact sleep [4] and that inadequate indoor air quality (IAQ), often indicated through high carbon dioxide (CO_2) levels, negatively impacts health and performance of building occupants [5, 6].

The link between IAQ and occupant health and IEQ and sleep suggests a need for investigating effect of IAQ on sleep parameters. However, as the review of Urlaub et al. [1] shows, such studies are scarce. Studies on bed-

side personal ventilation systems have been inconclusive on if such systems can significantly improve subjective thermal sensation and subjective as well as objective sleep parameters though results do show a positive trend for these systems [7, 8]. Observations from a single case study, involving an Alzheimer’s patient, showed that peak CO₂ levels in bedroom, above 800 ppm, coincided with patient’s restless behaviour while such behaviour could not be correlated with temperature or humidity levels [9]. Though this study involved only a single participant, the results were unambiguous.

A series of experiments over the past few years have focused on the effect of IAQ on sleep in student dorms [2, 10–12]. Conducting these field investigations in dorms ensured that all participants were housed in nearly equivalent rooms and that they were already accustomed to their environments, ensuring their normal sleep pattern was preserved [10]. These studies influenced the CO₂ levels in the bedrooms mostly by opening or closing windows, or by a ventilation fan that was controlled based on CO₂ levels [11].

High CO₂ concentrations have been well correlated with nearly the whole range of indoor pollutants [13]. Since occupants are the primary indoor source of both CO₂ and bio-effluents, measuring CO₂ in indoor environs is regarded as a suitable surrogate for overall IAQ [5]. While Dutch regulations require a CO₂ level below 1200 ppm in bedrooms, to obtain a proper indoor air quality, CO₂ levels of 800 ppm for healthy adults and a level of 600 ppm for people with health conditions are to be striven for to prevent health problems of the airways [14, 15]. A study from Denmark indicated that a majority of children’s bedrooms do not meet even the 1200 ppm criteria [16]. The current work was designed to be able to contribute to this less explored field of IAQ

impact on sleep of healthy adults, using CO₂ levels as an indicator for IAQ. Sleep parameters were evaluated using multiple, orthogonal measures, both subjective and objective. It was intended that in addition to studying the effect of CO₂ levels on sleep parameters, results would be used to appraise the study methodology and protocols, thus providing guidance for future studies of larger scales.

2. Methodology

A mixed method approach was used to study the sleeping environment under two different conditions. One condition was with an opened window or door (OPEN), the other with closed windows and door (CLOSED). To assess indoor environmental quality, measurements were executed to determine the CO₂ levels, temperature, background noise, and relative humidity in the bedrooms. Qualitative assessment of sleep was done using sleep questionnaires [17, 18], while quantitative assessment was done through actigraphy and sleep monitoring (using a Sensewear Armband) and movement detection (using a FlexSensor). Instead of always going for an open window, participants were free to use door opening in certain cases, to evaluate the effectiveness of door opening at lowering the CO₂ levels in the bedroom. This becomes important during winter when opening windows gets proscriptive due to indoor-to-outdoor temperature differences.

2.1. *Study participants and locales*

Eighteen persons (age < 30 years) participated in this study. Participants were recruited on voluntary basis. All participants were required to

sign an informed consent prior to getting involved in the study. During measurements, participants were not allowed to consume alcoholic beverages, as studies show alcohol influences sleep [19]. Participant assignment and study scheduling have been summarised in Figure 1. Participant demographics have been presented in Table 1.

Figure 1: Summation of the study’s scheduling

All participants were selected from around the Eindhoven area in the Netherlands. While participation was voluntary, we tried to recruit participants so as to obtain near similar building characteristics. Most participants lived in apartment type buildings. Detailed building characteristics can be seen in Table 2, with each building type being denoted by a letter. Later, through a set of on-line questions, participants were screened to ensure that none of them used any sleep medication, suffered from any sleep disorders, or had any other health issues that could affect sleep (e.g. recent surgery, asthma).

Constraints on availability of measurement equipments and time available for voluntary participation meant that during any given week, only six subjects could participate in the study and the study duration had to be six weeks, from October through December, 2015. This would imply three weeks of OPEN studies and three weeks for CLOSED. OPEN and CLOSED conditions were each assessed over five days during a week — Sunday evening

Table 1: Participant demographics along with survey duration and their building type

Sl. No.	Gender	Age	First condition	Door/Window	Building	Study dates	Flex sensor
1	Male	23	Open	Window	B	19-25 Oct, 9-15 Nov	No
2	Male	25	Open	Door	A	19-25 Oct, 9-15 Nov	Yes
3	Male	25	Open	Door	A	19-25 Oct, 9-15 Nov	Yes
4	Male	21	Close	Window	A	19-25 Oct, 9-15 Nov	No
5	Male	22	Close	Window	B	9-15 Nov, 30-6 Dec	No
6	Female	23	Open	Window	B	26-31 Oct, 16-22 Nov	Yes
7	Male	22	Open	Window	C	26-31 Oct, 16-22 Nov	Yes
8	Female	25	Open	Window	D	26-31 Oct, 16-22 Nov	No
9	Male	21	Close	Window	B	26-31 Oct, 16-22 Nov	Yes
10	Female	23	Close	Door	B	26-31 Oct, 16-22 Nov	Yes
11	Female	24	Close	Window	A	2-8 Nov, 23-29 Nov	Yes
12	Female	22	Open	Door	B	2-8 Nov, 23-29 Nov	Yes
13	Male	25	Open	Door	A	2-8 Nov, 23-29 Nov	Yes
14	Female	23	Open	Window	E	2-8 Nov, 23-29 Nov	Yes
15	Female	23	Close	Door	A	2-8 Nov, 23-29 Nov	Yes
16	Male	27	Close	Door	F	16-22 Nov, 30-6 Dec	No
17	Female	23	Open	Window	G	9-15 Nov, 30-6 Dec	Yes

to Friday morning — with no change in amount of people or furniture in the room. Participants in two-room dorms opened a door, instead of a window,

Table 2: Participant’s buildings characteristics

Building Code	Built year	Built type	Room size	Window orientation
A	1959	concrete	Floor area: 9 m ² ; For 1 participant, 22 m ² . Height: 2.7 m	East or West
B	1995–2000	concrete, brick	Floor area: 18 m ² . Height: 2.4 m; For 1 participant, 3.1 m	East or West
C	2004	concrete	Floor area: 20 m ² . Height: 2.5 m	East
D	1983	brick, terraced house	Floor area: 24 m ² . Height: 2.4 m	South
E	1930	concrete, brick	Floor area: 15.8 m ² . Height: 3 m	East
F	2014	concrete	Floor area: 15 m ² . Height: 3 m	West
G	1979	concrete	Floor area: 19.3 m ² . Height: 2.9 m	East

for ventilating the bedroom. The other 10 participants opened a window by placing a 10 cm long object in the window frame, to ensure a fixed opening area.

Subjectively assessed sleep parameters — feeling of rest, number of awakenings, sleep depth, length, latency, quality, and efficiency — were compared when considering all five day’s of data as well as after excluding the first day’s data. This was done considering the participants may have taken the first day to get used to the equipments. Comparisons of the data sets, with or without the first day’s data, did not yield significant differences (Wilcoxon test, p-values ranging between 0.41 and 0.99). Even so, the first day’s data was excluded when comparing subjective responses to be on the safer side.

2.2. Sleep characteristic assessment

2.2.1. Subjective assessment of sleep quality

The methods used to qualitatively and quantitatively assess sleep are enlisted in Table 3. Questionnaires were used to measure the qualitative sleep quality. The Pittsburgh Sleep Quality Index (PSQI) rates sleep over longer periods of time [20]. The PSQI was 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 [17]. A few questions of the Morning-questionnaire (Questions 2 through 5) were added to the GSQS, forming an online questionnaire (Figure Appendix A.1). These questions of the morning questionnaire were among other ratings of the depth of sleep and restfulness during the night. This online questionnaire was filled in by participants every morning.

Figure 2: Image of the sleep diary administered to participants daily. The Dutch terms, translated from left to right, mean: Day, Date, Time to bed, Time out of bed, Sleeping, In bed, without sleeping, Time when lights go out.

The sleep diary (Figure 2) was used to indicate when the participants went to bed, when they fell asleep and when they woke up. From the sleep diary sleep latency, length of sleep, number of awakenings, and sleep efficiency can be derived. Additionally, a comments section was given for further information. Sleep diary, PSQI, and GSQS were administered in Dutch as all participants were native Dutch.

Table 3: Sleep assessment methodology

Criteria	Variables	Unit /Range	Interpretation	Interval
PSQI		0–21	0 = good, 21 = bad (sleep quality)	Weekly
GSQG		0–14	0 = good, 14 = bad (sleep quality)	Daily
Morning Questionnaire	Rest	1–7	1 = not rested, 7 = fully rested	Daily
Sleep Diary	Depth	1–7	1 = not deep, 7 = very deep	Daily
	Sleep latency	min		Daily
	Length of sleep	hrs		Daily
	No. of awakenings			Daily
	Sleep efficiency	0–100%		Daily
Sensewear	Sleep latency	min		1 min
	Length of sleep	hrs		1 min
	No. of awakenings			1 min
	Sleep efficiency	0–100%		1 min
FlexSensor	Movements	0–300,000 V	Spikes = movement	5 min

2.2.2. Objective assessment of sleep quality

Actigraphy was used for obtaining an objective assessment of participant’s sleep. Actigraphy has the advantages of being economic, minimally intrusive from the participant’s viewpoint, and may be used over long terms [21]. In combination with subjective responses, it can provide data quality comparable to objective data obtained through polysomnography [22]. For actigraphy, the Sensewear Armband was used. All participants wore it on their upper right arm during nights. The Sensewear Armband is a clinically tested and validated multi-sensor body monitoring system, that goes beyond tra-

ditional actigraphy by also measuring skin temperature, heat flux, and skin galvanic response (for skin moisture levels) [23–25]. It calculates activity level and metabolism every minute, from which the sleep latency, length of sleep, number of awakenings and the sleep efficiency can be derived.

A Flexsensor (<https://www.antratek.nl/flex-sensor-4-5>) was used to observe the movement of the subjects during the night. This device could only be implemented for 12 subjects due to number of available sensors (Table 1). The Flex sensor’s resistance increases when it is bent. Thus it may be used to estimate restlessness during sleep, with spikes in resistance corresponding to participant’s restlessness during a night. The sensor was placed under the participant’s pillow.

Prior to starting the full schedule of measurements, background noise was measured by single point measurement, at 10 second intervals, with a spectral sound level meter. It was measured near the pillow, the window and the door, at sleeping position height. These measurements were performed during the evening, mostly between 6 and 10 pm. For one participant, background noise was measured at different points during the entire night, to analyse representativeness of the measured noise levels. In this single bedroom, background noise was measured under three conditions: just the window open, just the door open, and both door and window closed.

Measurements of CO₂, temperature and RH were logged at five-minute intervals. Where possible, sensors were placed about 1.5 meters from the participant’s head to avoid their directly breathing upon the sensors. Air velocity was not monitored on a continuous basis since preliminary measurements in the volunteers’ bedrooms showed that for both OPEN and CLOSED

air velocity remained ≤ 0.2 m/s. The specifics of the equipments can be seen in Table 4. The instruments were connected to a Grant Squirrel data logger through the SquirrelView platform. To give an idea to the reader of the set up, a schematic is presented in Figure 3. Time points when participants went to bed and woke up were ascertained using sleep diary entries. Objective parameters logged over this duration were compiled and used in the subsequent comparisons.

Figure 3: A schema of the bedrooms layout with relative positioning of the sleeper and sensors.

Table 4: Specifications of instruments used for IEQ assessment

Instrument	Output	Range	Accuracy	Interval
GW47 CO ₂ , RH, temperature sensor	0–5 V	0–5000 ppm CO ₂ ; 10 – 90% RH; 5.0–40.0 °C	±50 ppm CO ₂ ; ±2% RH; ±0.4 °C	5 min
RION, NL-32, Spectral sound level meter	L _A [dB(A)]	0-100 dB (20-12,500 Hz)	≤20 dB(A) in-herent noise	10 s

2.3. Analysis of responses

MATLAB R2014b was used for data collation and pre-processing. IBM SPSS Statistics 23 was used to analyse the data. Mean values for measured parameters are represented as mean (standard deviation). Initially, normality of the collected data was verified using the Shapiro-Wilk test. To test for significant differences, t-test was used for normally distributed parameters while Wilcoxon Signed-Rank test was used for non-normal data. Subjective sleep assessors were compared as an average, per participant, for OPEN against CLOSED. Objective sleep assessors and IEQ parameters were compared between OPEN and CLOSED as day wise averages (or day wise counts when considering restless periods or awakenings). To establish sufficiency of the experimental design, measured IEQ variables were tested against door versus window opening, building orientation or location, and room characteristics. Pearson product moment correlation (r) was also calculated between the assessed sleep parameters and the measured IEQ parameters. Linear regression analysis was used to examine multivariate correlations between sleep parameters and IEQ measures. All comparisons reported in the results are 2-tailed, at a 5% significance level. For the comparisons which yielded a significant difference in the 2-tailed test, subsequent 1-tailed tests were carried out. A short summation of the set-up for statistical tests is presented in Table 5.

2.3.1. CO₂ threshold value

We attempted to demarcate a threshold for CO₂ level, across which the measured sleep parameters showed significant differences. After dividing the entire set of measured data (both OPEN and CLOSED) by the day averaged

Table 5: Statistical analysis comparisons

Comparison	N
Objective measures	
OPEN vs CLOSED windows	49
OPEN vs CLOSED doors	32
Doors vs windows	32 vs 49
Background noise measurements	
OPEN vs CLOSED	10
Subjective measures	
OPEN vs CLOSED	17

CO₂ levels, in steps of 50 ppm, Wilcoxon rank test was used for comparing the sleep parameters. The comparisons were always carried out with respect to sleep parameters recorded under 800 ppm — in lieu of the findings from Cremers [9]. Thus, “< 800 vs > 800” implies a comparison of circumstances of CO₂ levels under 800 ppm to those of CO₂ levels over 800 ppm, “< 800 vs > 850” implies a comparison of circumstances of CO₂ levels under 800 ppm to those of CO₂ levels over 850 ppm, and so on. Comparisons were not carried out beyond 1250 ppm since the number of such data points were under 20.

3. Results

A histogram of CO₂ levels and indoor air temperatures measured in the bedrooms through the entire study for both OPEN and CLOSED cases, averaged over each night, is given in Fig. 4. Figure 5 summarises monthly outdoor temperature and wind velocity values, for the survey months of October through December 2015, in the Eindhoven area [26].

Figure 4: Frequency distribution of a) CO₂ levels and b) indoor air temperatures recorded in participant bedrooms

Figure 5: a) Monthly summary of outdoor temperature b) Monthly summary of outdoor wind velocity

3.1. IEQ parameters

Figure 6 a) shows the four-day average CO₂ levels, per participant, under both conditions. The average CO₂ levels were 731 ppm and 1147 ppm in the open and closed conditions, respectively. The CO₂ measurements are not normally distributed. OPEN and CLOSED gave significantly different levels of CO₂, with closed conditions having higher CO₂ levels, as intended by the experiment design ($p < 0.00001$). The four-day average for temperature, under both conditions, is shown in Fig. 6 b). To give the reader an idea regarding prevalent outdoor conditions during the survey months, the outdoor temperature and wind velocity have been summarised in Figure 5

(source [26]).

Average temperature at night was 19.4 °C indoors and 5.8 °C outdoors in the open condition. In the closed condition the temperature was 19.7 °C indoors and 7.1 °C outdoors. The indoor temperatures recorded were normally distributed and for OPEN and CLOSED, they were not significantly different ($p = 0.18$). Average relative humidity in the open condition was 56% (9%), compared to 55% (9%) in closed condition. These values were also not significantly different ($p = 0.871$).

Figure 6: Bedroom a) CO₂ levels b) Temperature c) Background noise, averaged over four participation days for all 17 participants

Average background noise, per subject, can be seen in Fig. 6 c). The average background noise level was 46.07 dB(A) for OPEN vs 40.53 dB(A) for CLOSED. Background noise levels were significantly higher for OPEN ($p = 0.008$).

3.1.1. Opening windows vs opening doors

Considering the cases which used door vs those which used windows for creating a difference in indoor CO₂ levels, we find that use of either method successfully creates a higher CO₂ concentration in CLOSED conditions ($p < 0.00001$). Also, for both door and window, OPEN or CLOSED do not lead to significant differences in temperature or relative humidity. For the one participant, in whose room sound levels were monitored continuously over a night, the situation with door open (min = 30.7, mean = 36.3, max = 42.4) was less noisy ($p = 0.002$) than when window was open (min = 34.4, mean = 41.6, max = 47.9 dB(A)).

In OPEN operation, window cases lead to significantly lesser CO₂ concentrations ($p = 0.0003$), while door cases lead to a lesser recorded indoor temperature, a difference of ~ 2 °C (mean temperature difference of 1.9 °C, $p < 0.00001$).

3.2. Subjective sleep questionnaires

Table 6 shows the results of sleep quality variables that are obtained from the questionnaires. None of the sleep quality variables recorded were normally distributed. Of all queried measures, only depth of sleep shows a significant difference between OPEN and CLOSED ($p = 0.0017$).

Table 6: Sleep assessment scores from questionnaires. O = OPEN, C = CLOSED

Criteria	State	Avg.	Min	Max	Criteria	State	Avg.	Min	Max
GSQS	O	3.18	0	13	Latency (min)	O	22.53	0	75
	C	2.96	0	11		C	22.41	0	75
Sleep quality	O	3.44	1	5	Length (h)	O	8.03	4.5	10.3
	C	3.38	0	5		C	7.86	4.8	10
Depth	O	4.21	1	7	Awakenings (no. per night)	O	0.65	0	3
	C	4.6	1	7		C	0.62	0	3
Rest	O	4.71	2	7	Efficiency (%)	O	87.7	51	97.5
	C	4.6	1	7		C	88.4	62	100

3.2.1. Correlation between subjective sleep parameters and IEQ parameters

Significant correlations found were between depth of sleep and CO₂ levels ($r = -0.16$; $p = 0.048$) and depth of sleep and temperature ($r = 0.21$; $p = 0.016$). The correlations thus found were not remarkable in magnitude. They, however, implicate that increasing CO₂ levels reduce depth of sleep.

In terms of multivariate relations, depth of sleep showed best correspondence with combination of temperature and CO₂ ($R^2 = 0.06$, $p = 0.008$) and length of sleep showed a significant correlation with combination of background noise and CO₂ ($R^2 = 0.21$, $p = 0.03$). The multivariate correlation found for subjective sleep depth corresponds to the univariate correlations discussed. Also of note is the fact that the temperature values recorded did not hold any correlation with the corresponding CO₂ levels ($p = 0.94$).

3.3. Objective sleep parameters

Objectively measured sleep parameters are presented in Table 7, with the ones measured using SenseWear Armband being marked as -SA and the one measured using Flexsensor being marked as -FS. None of the parameters in Table 7 exhibited a significant difference between OPEN and CLOSED. How-

ever, the mean of all four parameters were slightly better for OPEN. And this trend among the objectively measured parameters is consistent, unlike the mean values of the subjectively recorded parameters. Unfortunately, positioning the Flexsensor was an issue that could not be successfully addressed. The sensor often slipped off during the course of the night, leading to unusable readings. In Figure 7, we present the Flexsensor recorded resistance data’s frequency distribution of a single participant during the entire five days each of CLOSED and OPEN operations. This particular participant was chosen since the sensor did not slip off on any of the days in this case.

Table 7: Objective sleep assessment scores. O = OPEN, C = CLOSED

Criteria	State	Avg.	Min	Max
Latency-SA	O	22.6	0	106
(min)	C	23.2	0	100
Length-SA	O	8.1	4	10.8
(h)	C	7.8	4.8	10
Awakenings-SA	O	2.6	0	7
(no. per night)	C	2.7	0	8
Efficiency-SA	O	78.2	51	96.3
(%)	C	77.9	47.5	96.3
Awakenings-FS	O	2.4	0	7
(no. per night)	C	2.8	0	6

3.3.1. Correlation between objective sleep parameters and IEQ parameters

Number of awakenings was correlated with CO₂ levels ($r = 0.191$; $p = 0.014$) and temperature ($r = -0.160$; $p = 0.039$). Sleep efficiency correlated with CO₂ levels ($r = -0.199$; $p = 0.009$) and temperature ($r = 0.194$; $p = 0.029$). In terms of multivariate correlations, number of awakenings ($p =$

Figure 7: Frequency distribution of Flexsensor resistance data of a single participant, under open and close conditions

0.005; $R^2 = 0.06$) and sleep efficiency ($p = 0.001$; $R^2 = 0.08$) have a better relation with the combination of CO_2 and temperature.

While subjective evaluation showed a significant difference for sleep depth between OPEN and CLOSED, objective measurements did not show any statistically significant difference between OPEN and CLOSED conditions. Awakenings during a night reduce with lower CO_2 concentration and warmer conditions. An increment in awakenings leads to a decrease in sleep efficiency, since less time is spent sleeping.

3.3.2. Correlating objective and subjective assessment

Table 8 shows the average of sleep latency, length of sleep, number of awakenings, and sleep efficiency for both the questionnaire and the Sensewear results. As can be seen, although means of sleep length and latency do show similarities, the same is not true for number of awakenings and the sleep

efficiency. The Pearson correlation coefficient of the objective and subjective sleep parameters are also examined. As may be seen, all sleep quality variables show a significant p-value, even though ‘r’ values for the number of awakenings and sleep efficiency are rather low.

Table 8: Correlations between sleep parameters obtained from questionnaires (-Q) and Sensewear Armband (-SA)

Criteria	r (p-value)	Avg.-Q	Avg.-SA
Latency (min)	0.45 (< 0.001)	22.3	22.9
Length (h)	0.87 (< 0.001)	7.9	7.9
No. of awakenings	0.28 (< 0.001)	0.62	2.61
Efficiency (%)	0.15 (0.047)	88.1	78.1

3.4. A threshold value of CO_2 for sleep parameters

From objective and subjective assessments, we found that depth of sleep, number of awakenings, and sleep efficiency had a correlation with the CO_2 level. So, the attempt to demarcate a CO_2 threshold was made for these parameters. No distinctive patterns were noticed for sleep length (both subjective and objective) and subjective sleep efficiency.

The points of interest are represented as plots in Figure 8. The plots show (1-p) values and thus, at 5% significance level, the 0.95 level is marked with a red, dotted line. For all four plots in the figure, significant differences turn up when considering data points with CO_2 concentrations at 1150 ppm or over against the data points of below 800 ppm. It is possible that a similar pattern of distinction could have carried on but was not detectable in this study due to lack of enough data points over 1250 ppm.

Figure 8: a) Threshold distinction for sleep depth — from questionnaires b) Threshold distinction for sleep efficiency — from Sensewear c) Threshold distinction for number of awakenings — from Sensewear d) Threshold distinction for number of awakenings — from questionnaires

4. Discussions

Among the studies on how IEQ affects sleep, a large fraction deal with influence of temperature. An even smaller number of studies study the impact of IAQ on sleep quality using objective measures of sleep. Higher ventilation rates in bedrooms may give rise to symptoms associated with dry air — dry nasal cavity, lips etc. [11, 12]. While the results from different studies may vary in their details and may not always be statistically significant, the overall consensus pointed to lower CO₂ values improving self-assessed sleep quality, subjective perception of air, better wakefulness and ability to con-

centrate on the day after, and better actigraphy determined sleep efficiency. These conclusions were also broadly supported by the results of the current study. Measurements showed both the CO₂ levels and the background noise to be significantly different between OPEN and CLOSED conditions. Hence, any distinction in sleep parameters between OPEN and CLOSED may have had contributions from the noise level difference. These findings were true for using either doors or windows

Open windows do impact the bedroom indoor differently than open doors. Indoors were warmer with open windows (Section 3.1.1). The later finding relates to the warmer outdoor conditions during carrying out the OPEN window observations vs OPEN door observations. Outdoor minimum temperatures were warmer by 0.7 °C, on average, when windows were open, compared to door opening. While opening a window leads to a direct influence of outdoors on the bedroom temperature, opening the door into the house interior does not have a similar effect from outdoors. Open windows lead to bedroom interior conditions being closer to outdoors than when using just open doors. For CLOSED operation, the CO₂ concentrations ($p = 0.54$) were not significantly different between door and window cases. However, the temperature values were again warmer for window cases (mean temperature difference of 2.3 °C, $p < 0.00001$). This is also ascribable to the open door situation harmonizing bedroom conditions with the rest of the house. These findings would imply that opening a door or a window certainly leads to better ventilation, as implied by reduced CO₂ levels, than having all openings closed. Additionally, a finding that was not the purpose of this study was that opening a window is better at reducing CO₂ levels and at harmonising

the indoor thermal conditions with outdoors. So, when outdoor conditions are not in the extremes of warmth or cold, opening the window for reducing CO₂ levels is a better choice. For non-conductive outdoor conditions, it is better to open the door since door opening ventilates the bedroom well enough while harmonizing the thermal conditions with the moderate indoors of the whole house. A further reasoning for choosing door over window may be related to the noise levels in the surrounding areas as well, since door opening may be significantly quieter than window opening.

The improvement of sleep depth with lower CO₂ concentrations, as discussed in Section 3.2.1, corresponds to similar results found by Laverge and Janssens [10]. Also, within the range of temperatures recorded in this study (Figure 4 b), warmer conditions lead to deeper sleep. The beneficial effects of comparatively warmer conditions on sleep ($\sim 23\text{--}26\text{ }^{\circ}\text{C}$) have been observed in previous works as well [27, 28]. As opposed to the one-to-one correlations, the nature of the multivariate correlation with sleep length is more difficult to comment upon. It would seem that length of sleep increases with higher background noise and greater CO₂ concentrations. Sleep length is a complicated variable to correlate with environmental parameters since there are the confounding factors of subject’s life style and preferences. Additionally, sleep quality and quantity are considered to be orthogonal quantities that may not be correlated with any confidence [18, 21]. Previous studies, using similar methods for creating variations in bedroom CO₂ levels, have noted both improved sleep quality on GSQS (non-significant) [12] and reduced sleep quality on GSQS [10]. Our study did not discern a significant difference on the GSQS between OPEN and CLOSED, though on average the OPEN GSQS is better

(Table 6).

The use of Flexsensor for objective monitoring of sleep quality was an innovational approach employed in this study though the implementation was not flawless and we could not obtain convincing data for several participants. For the example dataset that was complete, assuming higher resistances correspond to a more restless sleep, the frequency distribution in Figure 7 suggests that Flexsensor readings also indicated a more restless sleep under CLOSED conditions. This gives us confidence that when implemented successfully, the Flexsensors (or a similar technology to detect a sleeping person’s movement) may be useful for objectively distinguishing sleep quality. Further, while the sensor slipped off about 54% of the CLOSED cases, it slipped off only 32% of the OPEN days. This statistic may be interpreted as an indirect measure of restlessness in closed conditions, assuming restlessness is the primary factor behind the sensor slipping off.

The multivariate correlations discussed in Section 3.3.1 show that sleep efficiency significantly increases with a lower CO₂ levels and warmer temperatures. The results from Strøm-Tejsen et al. [11] had a similar trend in the sense that in their case, sleep efficiency improved (non-significantly) with open windows. But unlike their results, where sleep latency reduced with open window, we do not detect any significant correlation of any measured environmental parameter with sleep latency.

We make an effort to demarcate a CO₂ threshold level for sleep quality. The results are presented in Section 3.4 and they show a distinct possibility that sleep of healthy adults in indoor environments of CO₂ concentrations over 1150 ppm is likely to be compromised. This is a higher level that found

by Cremers [9] and is quite possibly because our study involved healthy adults. Thus, it would also seem that sleep parameters of healthy adults are more resilient to worsening IAQ conditions. This implies that vulnerable populations would need more detailed and careful attention.

An important finding from this study was the level of correlations between objective and subjective measures of sleep parameters. This is significant for designing further such investigations. In subsequent studies, the dependence on subjective questionnaires may be reduced, especially for ascertaining quantitative aspects of sleep. This would appreciably reduce questionnaire length and hopefully improve fidelity of participant responses.

4.1. Study design and limitations

4.1.1. Measuring sleep parameters

Our investigation employed multiple, orthogonal methods to assess sleep quality. Occasionally participants missed out on filling the online questionnaire while the sleep diary on paper was filled regularly. This suggests that for ensuring participant feedback, paper based questionnaires may be the better alternative. Analysis of the results showed that though there were differences between objective and subjective sleep quantity indicators — length, latency, efficiency, and number of awakenings — appreciable (and significant) correlations exist between the objective and subjective findings, specifically, the questionnaire responses and the readings from the Sensewear Armband. The correlations imply that the subjective and objective measurement techniques may be used in tandem, to compliment each other. Participants may not always be able to provide a precise description of their sleep nature on the morning after. However, it would seem that the basic trends that the

participants notice are also reflected in the objective measurements. At the same time, subjective assessment is a necessity for examining sleep quality. Hence, we suggest the use of a shorter subjective questionnaire, focusing on sleep quality, in conjunction with the Sensewear Armband, for a comprehensive valuation of sleep. This is similar to the suggestion of Kushida et al. [22].

Restlessness during sleep is difficult for participants to indicate in the morning-after questionnaires. Cremers [9] dealt with this issue by having a caretaker monitor sleep pattern of the individual. This aspect could be effectively dealt with by use of the Flex sensor, by giving a numeric value to number of major restless episodes during the night. Unfortunately though, we could not appropriately address the issue of positioning the Flex sensor in a manner so as to avoid its slipping off during the night. From the limited number of results that we do manage to gather, the number of restless events during OPEN and CLOSED are not significantly different. We do however note that the sensor is more prone to slipping off during CLOSED conditions. The results thus are inconclusive but encouraging. Further studies would need to focus on the set-up of the Flex sensor to make its successful use.

Our analysis suggested that a period of participants adjusting to the measurement condition may not be necessary. Even so, we excluded the first day’s subjective feedback from analysis. Future studies may also rely on a similar exception and accordingly design the experiment scheduling.

4.1.2. Experimental design

Using the “pwr” package of R [29], tests were conducted to examine power of the comparisons carried out in this work. Power of t-tests are examined,

with a note of caution that Wilcoxon test has slightly smaller power than t-test. For the subjective feedback, since there were 17 participants on whose responses pairwise tests were conducted to distinguish between OPEN and CLOSE, at a 5% significance level, this gives a power of 0.5 for detecting medium sized effects and 0.87 for detecting large size effects. Thus, it is definitely advisable to recruit more number of volunteers for future studies. That would imply either an extended study duration or use of greater number of equipment sets. Since extended study duration would also introduce outdoor conditions variability into the mix, this decision needs careful consideration.

The study design managed to achieve a distinction in CO₂ levels, as intended, by relying on opening and closing of available, occupant controlled openings in the buildings. We also used the measured CO₂ concentration, along with occupancy of the bedrooms, to estimate ventilation rates during OPEN and CLOSED. these values were also significantly different ($p < 0.00001$), irrespective of building type, room size, or opening type. We have not presented the ventilation rate data separately since it was a derived quantity (from CO₂ measurements) and not a directly measured one.

While achieving significant difference in CO₂ levels, the design also created significant differences in background noise levels, though temperature and humidity levels did not vary significantly between OPEN and CLOSED. However, the lack of any significant correlation of sleep parameters with noise levels suggests that any difference found in sleep parameters may be chiefly due to the IAQ difference. It may also be noted that number of instances of CO₂ levels over 1200 ppm were not too frequent. To establish thresholds levels of CO₂ as related to sleep, future studies would need to consider

sleep conditions with a wider range of CO₂ levels and for this, artificially introducing CO₂ in the environment may be necessary.

The subjects were aware of the intervention and its nature. This could have influenced their subjective responses. Further investigations would need to consider mechanical ventilation, with silent fans to create IAQ differences in the bedroom environment. Another remedy could be greater reliance on objective measurements. As our results suggest, the objective and subjective findings were well correlated, thus justifying a reliance on objective methods.

Since we were looking into sleep duration and quality, it would have been useful to measure the daylight exposure of the participants. Unfortunately, this could not be undertaken. A presumption made was that all participants had similar levels of daylight exposure — which is easily challenged.

Like a few previous studies [2, 10–12], all our participants were also young students. Their irregular life style and sleeping pattern could have reduced the likelihood of obtaining relevant results. Further studies should consider recruiting adults with more regular lifestyles. As our studies were conducted in normal residences, instead of student dorms, we thus verify the feasibility of such studies in other similar residences as well.

Opening the window vs opening the door had an effect on the indoor temperatures recorded and this has been discussed in Section 3.1.1. The IEQ parameters measured (temperature, RH, noise, and CO₂ levels) did not correlate with the building types (Table 2) or if a specific building was located close to a major street. However, CO₂ levels and noise levels correlate with the room size. In bedrooms with a volume larger than 50 m³, the average CO₂ level was 721 ppm while it was 1032 ppm in the bedrooms smaller than

50 m³. Similarly, the larger bedrooms had average sound level of 47.40 dB(A), while it was 41.59 dB(A) in bedrooms smaller than 50 m³. It would hence seem pertinent that when such studies are extended to residences, bedrooms of nearly similar size are chosen.

A limitation of the study was that clothing resistance of the sleeping participants was not estimated. This could have helped us better understand any confounding effects of the thermal environment on sleep parameters. Future studies may need to consider reliable methods for extracting data that may be used to estimate clo value of the sleeping participants. Whether participant recollection in questionnaires, on the next morning, may be taken as a suitable method for this needs to be better examined.

5. Conclusion

This work intended investigating the influence of bedroom air quality, as signified by CO₂ levels, on different sleep parameters. To this effect, subjective and objective measurements of sleep quality were carried out while the IAQ was influenced by using occupant operated openings (doors and windows). Results show that under OPEN condition, CO₂ concentrations were significantly lower ($p < 0.00001$). Qualitative information, obtained using subjective questionnaires, only indicated a significant difference in self-assessed depth of sleep between OPEN and CLOSED. Subjectively assessed sleep depth and length correlated with CO₂ levels. Objectively measured sleep efficiency and number of awakenings also correlated to the CO₂ levels measured. Lower CO₂ levels implied better sleep depth, sleep efficiency, lesser number of awakenings, but longer sleep duration. A finding with ma-

jor possible significance for future studies was that values of sleep parameters recorded by objective and subjective methods, correlated well with each other. This should help further establish the role of actigraphy in studying sleep. Analysis of the OPEN and CLOSED data sets taken together indicates that for bedrooms of healthy adults, CO₂ concentrations of 1100-1150 ppm may act as a watershed point, beyond which, sleep quality is quite liable to deteriorate. Further studies would be needed to more concretely establish a more precise demarcating concentration. At the same time, it would be advisable to independently study effect of IAQ on sleep quality of vulnerable populations like, young children and ageing adults. A special focus could be laid on children with ADHD and elderly people with any psychogeriatric disorder.

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Appendix A. Online questionnaire

Ochtend vragenlijst

Nederlandse versie

1. DeelnemersNummer

2. Hoe beoordeel je je slaapkwaliteit van de afgelopen nacht?

Denk hierbij aan inslaaptijd, aantal ontwakenen 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= Dromeloos, 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

Figure Appendix A.1: Representation of the online questionnaire administered to participants

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