Webinar: Sleeping Environment IAQ and Sleep Quality | 12 January 2023 (10:00-11:30 CET)

Questions from the audience

Questions for Chandra Sekhar (NUS, SG):

1. In the table I see only one situation with 2 occupants. How does this affect the required ventilation rate? Is this, with the MV for instance, 0.6 per person?
    - **A:** I presume you are referring to Slide 22 that shows the "number of occupants" in each of the 11 Sets of experiments. There is only one experiment (Set 6) in the NV study that we had 2 occupants - the idea was just to get an increased CO2 build-up overnight before conducting the CO2 decay and ACR computations the following morning.
2. Quite interesting to see the effects of combined trickle vents and mechanical extracts combined. In my studies in the UK I found that these extracts are turned off due to noise. In addition, modern homes are smaller than traditional homes. My question to you is whether you have any insights on the effect of bedroom volumes (i.e. should we be building higher ceilings to contrast extract failure?)
    - **A**: https://youtu.be/lFpn7ETaTQM
3. Does the size and sex (male/female) of the occupants affect the CO2 levels in the bedroom? Did you take these factors into consideration?
    - **A**: The simple answer is YES. Basal Metabolic Rate (BMR) varies as a function of sex, age, and body mass. More details can be found in the following reference: https://doi.org/10.1111/ina.12383
      In our paper https://doi.org/10.1080/23744731.2020.1845019, we had not taken these into consideration.
4. You said that location of the sensors is important to estimate ventilation rates. So, if I understood it right, the sensors should be installed close to a sleeping person? But shouldn't we install sensors in different parts of the room?
    - **A**: https://youtu.be/lFpn7ETaTQM
5. Are there any individual differences in terms of personal preferences?
    - **A:** Not sure if this question is directed to me. In any case, I will attempt to provide an answer. Yes, there will always be individual differences in terms of personal preferences. In office/work-place settings, we find that every occupant has his/her own preferences when it comes to the environmental conditions, which has also led to the notion of Personalized

Environmental Control Systems (PECS). PECS is also valid in sleeping environments.

6. CO_2 is heavier than air, so will high level extract be more effective?
    - **A:** In my view, a well-designed extract strategy is critical. If it is a high level extract (i.e. high ceiling room), there must be adequate driving force (within the room) for the warm air (with the contaminants) from the breathing zone to reach and be extracted. Of course, a mechanical exhaust would always be a better option. It is always about the room air distribution making use of the “PUSH” (supply) - “PULL” (exhaust) principle to be effectively functioning.
7. Comment: we should first look at what local building code requires (that is must to follow), then standard could be linked to code (not as typical in Nordic countries). Finally, we also have design recommendations (e.g. Finland) for airflow rate in different rooms (bedroom also).
    - **A:** Noted with thanks. Appreciate the comment.
8. The new regulations (in Sweden) tend to move away from giving numbers, just stating an acceptable indoor environment should be achieved, however, praxis from older regulations in Sweden say that fresh airflow in bedroom should be 4 l/s person, maybe there are "hidden" praxis in other countries as well, is this anything you have encountered?
    - **A:** In principle, I agree with the suggestion. This is a performance-based approach as opposed to a prescriptive approach. However, the challenge with a performance-based approach is that it is perceived to be more difficult to practice or implement. How does one define an acceptable IEQ performance of a sleeping environment? We need to come up with some metrics to address this and we are not quite there yet. As I said in my presentation, perhaps a prescriptive requirement (with a ventilation rate l/s per person etc.) may well have to be seen as a minimum. At this time, not many countries globally even have such a requirement for bedrooms.

Questions for Li Lan (Shanghai Jiao Tong University, CN):

1. Did you perform or are you aware of studies on sleep quality at high temperatures and low humidity? E.g., T > 30 C and RH < 30%.
    - **A**: https://youtu.be/lFpn7ETaTQM
2. Have you studied the effect of ceiling fans?
    - **A**: https://youtu.be/lFpn7ETaTQM
3. Sleep quality is defined by balance of light, REM and deep sleep. Has anyone researched how CO_2 and temp levels influence this balance?
    - **A**: https://youtu.be/lFpn7ETaTQM
4. Are there any individual differences in terms of personal preferences?

- **A:** There are individual differences in terms of personal preferences, these preferences include sleeping habits and adjustment of bedroom environment, for example, usage of bed coverings, clothing and fans, all of which will affect heat transfer between human body and environment, and thus the exact value of thermal neutral temperature for sleep. However, it is for sure that at high temperatures (>30^{o}C), there are few personal preferences. In addition to the thermal balance aspect, there is an intrinsic relationship between temperature and neural activity. We have observed that temperatures at the lower end of the thermal comfort range are more beneficial for cognitive performance [1], probably because our nervous system controls thermoregulatory effectors depending on whether signals are sent by warm or cold cutaneous thermal receptors. Our nervous system should also have such effector-specific activity during sleep.
  [1] Li Lan, Jieyu Tang, Pawel Wargocki, David P. Wyon, Zhiwei Lian. 2022. *Cognitive performance was reduced by higher air temperature even when thermal comfort was maintained over the 24-28 degrees C range*. Indoor Air, 32: e12916.

5. What are the main or key sleep parameters to understand thermal comfort during sleep? Is there any review study related to this?
   - **A:** Normal human sleep is comprised of two states - rapid eye movement (REM) and non-REM (NREM) sleep - that alternate cyclically across a sleep episode. Sleep begins in NREM (usually stage N1) and progresses through deeper NREM stages (stages N2 and N3) before the first episode of REM sleep occurs approximately 80 to 100 min later. Light sleep is the term for sleep that falls into the categories of stage N1 and stage N2. The stage N3 sleep is characterized by slow wave activity (brain waves of frequency 0.5 Hz-2Hz), thus is referred as slow wave sleep (SWS) or deep sleep.
     The sleep quality statistics that are calculated based on sleep measurement include: Total sleep time (TST), Sleep efficiency (SE), Sleep onset latency (SOL), Wake time after sleep onset (WASO), Duration or Percentage of each sleep stage of each sleep stage. Lower SE, lower duration of N3 or REM sleep, longer SOL, and/or higher wake time indicate poorer sleep quality.
     Following are three review papers on thermal environment, including one of mine:
     [1] K. Okamoto-Mizuno, K. Mizuno. *Effects of thermal environment on sleep and circadian rhythm*. J. Physiol. Anthropol. 31 (2012) 14.

[2] Zachary A. Caddick, Kevin Gregory, Lucia Arsintescu et al. *A review of the environmental parameters necessary for an optimal sleep environment*. Building and Environment (2018), 132:11-20.
[3] Li Lan, Kazuyo Tsuzuki, Yanfeng Liu, Zhiwei Lian. 2017. *Thermal environment and sleep quality: A review*. Energy and Buildings, 149: 101-113.

Questions for Jelle Laverge (Ghent University, BE):

1. I have done some research on CO2 levels between different rooms during night sleep and I have found that it depends on the house and the natural air flow indoors without HVAC and with all the windows closed.
    - **A:** This is very true, the variability is high. That is also why, as Chandra showed, having dedicated devices that ensure the appropriate flow rate for a specific room (at least one mechanical component for supply or exhaust) is important for a robust ventilation strategy

Questions for Pawel Wargocki (ICIEE/DTU, DK):

1. Should we use wearables and even EEG to track sleep patterns and environment through the night?
   PAW: There are some limitations when using wearables. We will be publishing the paper soon. We should be aware of these limitations. Wearables will give fairly good information about sleep length, sleep efficiency, awakenings and sleep onset latency. I recommend to use subjective sleep quality ratings such as Gronningen Sleep Quality Scale. There are few others. They need to be verified.
    - **A:** https://youtu.be/bkJEm1bGhE8
2. Did you have some results for emission rates of CO2 during the night per person, compared to EN TR 14788?
   The mentioned standard suggests to us 12 L/h per person. Our data indicates slightly lower numbers but the difference is rather small. We are somewhere around 10-12 L/h per person independently of age. Awakenings at night and increased light sleep may increase emission rates and we are about to examine it.
    - **A:** https://youtu.be/bkJEm1bGhE8
3. I now see Pawel has used a sleep tracker. Doors and door opening is recommended and in addition should we recommend that hotels do have opening windows as many today are sealed . They usually are air conditioned but our unpublished survey indicates hotel customers are frustrated if they cannot have the option of opening a window.
   PAW: Adequate mechanical ventilation should provide ventilation without the need to open windows. In many hotels windows are closed to save energy for

cooling when AC is running. Also in many of them AC is considered a means of ventilation whereas it only provides a cooling effect.
    - **A:** https://youtu.be/bkJEm1bGhE8
4. Will we need to keep under 700-800/ 1100-1200 ppm all night?Is it OK if we keep the mean value for the night?
   PAW. Yes, CO2 should best remain below 700-800 ppm
    - **A:** https://youtu.be/bkJEm1bGhE8
5. Should the 750 or 1200 ppm (or whatever) limit be a limit or an overnight average?
   PAW. Yes, see my comment above
    - **A:** https://youtu.be/bkJEm1bGhE8
6. Comment: threshold of 700-800 ppm has also been observed for more restful sleep for an Alzheimer patient. No snoring, no apnoea, no panic
   PAW: We are aware of this research. So far we looked at the sleep quality of healthy people. Of course people who are unhealthy and have sleep problems can be even more affected by poor bedroom IEQ. We should examine this in the future.
    - **A:** https://youtu.be/bkJEm1bGhE8
7. Comment: 700ppm 200 years ago is not 700 ppm today though!
    - **A:** Correct. 1000 ppm is neither
8. On one point, I have a difficulty to find an explanation to the recommendation to supply outside air versus an open door bedroom.
   Indeed, when we sleep with an open door bedroom the CO2 level stays very low since the CO2 will migrate to the rest of the dwelling space. Nevertheless, your research claims there is no benefit on sleep quality when only the door is open even though the CO2 level stays low during the night. So, what would be the explanation to justify that an open door doesn't help sleep quality?
    - **A:** We provided explanation to your question in the Discussion of our paper. I am attaching the quote below. Briefly, we are working with two hypotheses:
        i. Opening the door to bedroom will provide dilution but the effect is insufficient to avoid the disturbance to sleep. Please note that our tentative relationship between CO2 and sleep quality defines the levels of 800 and 1200 ppm. So if CO2 stays about 1200 ppm or even above 800 ppm there may be no effect on sleep quality even though the pollution was diluted.
        ii. Opening the door to bedroom reduce the level of CO2 but not the levels of other pollutants so the air quality level is not changed a lot. In our study we observed that perceived air quality did not improve when doors were open which would confirm the above hypothesis.

If air quality is not improved then no improvement for sleep quality either. What we think is that the air quality in the dwelling is fairly uniform so when you open the door co2 will be reduced as the main source of co2 at night is in the bedroom and co2 levels in other spaces are much lower. Therefore no benefit will be obtained.

improvements were seen when the doors were open. We believe that door opening did not provide adequate removal and dilution of pollutants in bedrooms even though we were not able to confirm this hypothesis with the limited measurements that were made. The reduced levels of CO_2 when the doors were open suggest that air from other parts of the dwelling was either drawn or diffused into the bedrooms. The CO_2 concentration of this air was low during the sleep period, as other spaces in the dwelling were not occupied, and consequently the bedroom CO_2 concentration was reduced, though not by as much as when the windows were open (Table 3).

As shown in the review by Canha et al., bedroom air during sleep contains numerous pollutants whose levels are higher than the limit values prescribed by the standards and guidelines [15]. These pollutants can enter bedrooms from other parts of the dwelling [30]. For example, cooking oil fumes originating from the kitchen were associated with overall poor sleep quality [52]. Additionally, exposure to increased PM_{10} concentration was significantly associated with increased obstructive sleep apnea [53], which may disturb sleep. A recent cross-sectional study showed that sleep stages were affected during exposures to NO_2, $PM_{2.5}$, and O_3; as a result some decreases in cognitive capacity were observed [54]. Finally, Chen et al. concluded that long-term exposures to $PM_{2.5}$, PM_{10}, and NO_2 were associated with poor sleep quality in rural China [55]. If proper removal or dilution of these and other pollutants is not achieved by the air that enters bedrooms, no improved bedroom IAQ and sleep quality should be expected. This may have been the case when the internal doors were open in the present study, even though the total concentration of VOCs was lower. On the other hand, window opening was able to provide sufficient dilution and removal of some of these pollutants. For example, the present study showed that the total concentration of VOCs and PM_{10} levels were lower and perceived IAQ was improved when the windows were open. However, window opening increased NO_2 concentration, which thus presumably originated outdoors. This could counteract the positive effect of reduced exposure to other pollutants because exposure to NO_2 can increase the risk of sleep apnea [56]. Future studies should closely look at the impact of outdoor air pollution on sleep quality and consequently

9. In the take-aways from Pawel Wargocki, he concludes that the CO2 should ideally be between 700-800 ppm or at least 1100-1200 ppm in bedrooms. As he also mentions a lot of articles (existing or in production), could it be possible to know which specific research work and references support this conclusion.

- **A:** I attach a few papers that provide support to the proposed relationship. Please note that it is TENTATIVE. All other research we have performed in the last three years provides some support to our recommendations. I also attach one paper that is discussing it. But of course we need more work. We also need to understand what pollutants play the role in disturbing sleep. CO2 is only the marker.
  i. Xiaojun Fan, Mitsuharu Sakamoto, Huiqi Shao, Kazuki Kuga, Kazuhide Ito, Li Lan, Pawel Wargocki. *Emission rate of carbon dioxide while sleeping*.International Journal of Indoor Environment and Health. August 2021. https://doi.org/10.1111/ina.12911
  ii. Xiaojun Fan, Chenxi Liao, Mariya P.Bivolarova, Chandra Sekhar, Jelle Laverge, Li Lan, Anna Mainka, Mizuho Akimoto, Pawel Wargocki. *A field intervention study of the effects of window and door opening on bedroom IAQ, sleep quality, and next-day cognitive performance*. Building and Environment. Volume 225, November 2022. https://doi.org/10.1016/j.buildenv.2022.109630
  iii. Chandra Sekhara, Mizuho Akimoto, Xiaojun Fan, Mariya Bivolarova,Chenxi Liao, Li Lan, Pawel Wargocki. *Bedroom ventilation: Review of existing evidence and current standards*. Building and Environment. Volume 184, 15 October 2020. https://doi.org/10.1016/j.buildenv.2020.107229
  iv. Mizuho Akimoto, Chandra Sekhar, Mariya P. Bivolarova, Chenxi Liao, Xiaojun Fan, Jelle Laverge, Li Lan, Pawel Wargocki. *Reviewing How Bedroom Ventilation Affects IAQ and Sleep Quality*. ASHRAE Journal - April 2021 [56 - 57].