Residential Buildings Committee (RBC) Residential Issue Brief:

Ventilation, IEQ and Sleep Quality in Bedrooms

The Issue

Sleep is essential for health and well-being. We spend a major part of our life at home, about a third in bedrooms, which gets much higher for vulnerable populations like babies and the elderly. This holds even greater significance in lockdowns, as evidenced during the unprecedented COVID-19 global pandemic. As a general principle, sleep hygiene recommendations tend towards maintaining a cool, dark and quiet sleeping environment. A 2018 review attempted to define environmental conditions in sleeping environments for optimal sleep quality and proposed temperature and humidity ranging generally between 17-28 °C and 40-60% RH, all forms of noise being less than 35 dB, complete darkness and avoidance of blue light immediately before and during sleep, ventilation using sea-level air quality, and passive design using architectural features to incorporate the above elements into bedroom design (Caddick et al., 2018).

Based on a systematic literature review, the National Sleep Foundation expert panel, whilst noting that there were no tools or measures of sleep satisfaction applied to the general population and directly associated with good health, made some significant determinations concerning sleep quality: (a) Appropriate sleep satisfaction elements include how an individual feels about their sleep, immediately after their sleep, and during the subsequent day; (b) Sleep environmental factors include bedding comfort, bedroom temperature, noise and light; (c) Sleep initiation entails the time taken to fall asleep; (d) Maintenance parameters include the ease with which one falls back to sleep after awakening during a sleep period, amount of sleep on all days, and undisturbed sleep (Ohayon et al., 2018). A quality sleep for rejuvenation, good health and well-being to each of us is much more than just finding a bed and a place to sleep. Increasingly, in a fast-paced urbanized world, this is not easy to come by.

Sleep architecture is an important measure of the sleep quality and refers to the basic structural organization of normal sleep. There are two types of sleep, non-rapid eye-movement (NREM) sleep and rapid eye-movement (REM) sleep. NREM sleep is divided into stages 1, 2, 3, and 4, representing a continuum of relative depth and each has unique characteristics including variations in brain wave patterns, eye movements, and muscle tone.

Another recent review observed inadequate bedroom ventilation, poor IAQ and inadequate ventilation standards in many parts of the world and reported mean bedroom CO_2 concentrations ranging between approximately 430 ppm and 2600 ppm, and the mean bedroom air change rates from 0.2 to 4.9 h^{-1} (Sekhar et al., 2020). The measured results suggested that the ventilation rates were lower during heating seasons, especially in naturally ventilated bedrooms as well as bedrooms where air conditioning

Residential Issue Briefs are developed and approved by the ASHRAE Residential Buildings Committee (RBC) to address significant emerging topics. Ventilation, IEQ and Sleep Quality *was approved by the RBC on June 17, 2022.*

(with or without mechanical ventilation) was in operation. It was additionally observed that bedroom temperatures were lower during heating seasons. There is scanty information on whether the reported ventilation rates would disturb sleep quality. A few studies that have been performed suggest that sleep quality will not be negatively affected when bedroom ventilation rates are such that CO_2 levels remain below 750 ppm, while ventilation rates allowing CO_2 to increase about 1,150 ppm can disturb sleep quality and above 2,600 ppm can additionally reduce the next-day cognitive performance. Several air pollutants in bedrooms, such as PM2.5, could typically exceed the limit values established by guidelines or legislation, indicating that an effort should be made to minimize human exposure to air pollutants (Canha et al., 2021). Thermal, ventilation and IAQ requirements in standards and guidelines are inadequate and rarely have specific requirements for bedrooms (Sekhar et al., 2020). Consequently, our bedroom environments are far from ideal when it comes to thermal comfort and IAQ optimal for sleep.

There are several studies that described thermal comfort, ventilation, IAQ and sleep quality in various climatic conditions. They pertain to thermal comfort related behavioral adjustments, ventilation types and benefits of window/door opening towards improved air change rates and IAQ [CO_2, PM2.5, VOC and others] and bed environmental control involving local body cooling (Wang et al., 2021; Mishra et al., 2018; Liao et al., 2021; Akimoto et al., 2021; Sekhar et al., 2020; Algarni et al., 2021; Lan et al., 2018). Analogous to non-residential buildings where a trained professional Facilities Management (FM) team is responsible for ensuring optimal thermal comfort and IAQ for the health and well-being of occupants, it can be argued that residential buildings in general with the exception of elderly/nursing homes and social housing, and bedroom environments in particular, are left solely to the limited actions of the untrained and less knowledgeable individual users to bring about behavioral adjustments for their thermal comfort and IAQ.

Noise in bedrooms can be the result of technical systems such as noisy ventilation or air-conditioner, as well as can be transmitted between rooms or from outdoors especially when windows are kept open to ensure proper ventilation. Sleep can be significantly disturbed, both in terms of physiological and self-reported measures, during nights with noise levels exceeding 45 dB (Smith et al., 2019). There are a few studies that show associations between various night-time noise exposure indicators and sleep quality (Meng et al., 2020; Bartels et al., 2021; Roosli et al., 2019). Nocturnal aircraft noise exposures decrease the objective quality of sleep parameters both for noise levels and the number of noise events, such as those exceeding a given threshold (Nassur et al., 2019). White noise is purported to mask disruptive noises in the bedroom environment and be a non-pharmacological approach for promoting sleep and improving sleep quality (Ebben et al., 2021). However, a systematic review examining the relationships between continuous white noise or similar broadband noise and sleep (PROSPERO 2020: CRD42020148736) described sleep onset latency, sleep fragmentation, sleep quality, and sleep and awake durations as the primary outcomes (Riedy et al. 2021). Bedroom noise is also an issue with vulnerable populations involving elderly and patients with psychiatric and advanced cancer treatments (Desaulniers et al., 2018; Veale et al., 2020; Bernatchez et al., 2020). Noise is an easily identified environmental parameter that most people can relate to, and given the opportunity in a bedroom environment, would inevitably intervene through personal behavior to eliminate or minimize the noise level, such as closing the windows to cut down sound transmission from the exterior.

Light has dramatic effects on sleep, influencing circadian rhythm, melatonin production, and sleep cycles (Suni, 2020). Daily light exposure, including the type of light we see as well as when and how long we are exposed to it, has a critical effect on sleep. The bedroom environment must be as dark as possible and

devoid of electronic devices to improve sleep quality. In a study involving Israeli adults, it was found that excessive exposure to digital media devices at night-time was associated with longer sleep latency and decreased sleep hours (Green et al., 2018). In vulnerable groups, such as elderly population, higher pre-awake light (PAL) exposure was found to be significantly associated with a higher prevalence of sleep disturbances, independent of post-bedtime light exposure (Obayashi et al., 2019). Light, too, is generally an easily identified environmental parameter for which individual users can bring about personal interventions to create the optimal condition in the bedroom environment, such as drawing the curtains to eliminate visual discomfort due to external lighting and switching off the lights in the bedroom.

A recent COVID-19 related multi-disciplinary literature review involving peer-review papers from environmental psychology, building science and architecture relevant to quality of life in urban high-rise housing, and relevant newspaper and magazine articles involving COVID-19 impact on housing, identified synergies between passive design strategies and health-enhancing architecture or "restorative environmental design" principles (Peters et al., 2021). Among other findings of this study, bedroom design for restful sleep that contribute to circadian regulation and rooms with better indoor air quality focusing on natural ventilation, are noteworthy.

A peaceful night's sleep is vital for the next day's productivity and lower productivity is an economic loss. In an article for the NIH, Don-Wook, et al. describes Health Related Productivity Loss (HRPL) "The most important health conditions in order of their magnitude of induced burden of productivity loss were fatigue, neck or shoulder pain, insufficient sleep, back pain, headache, common cold and flu, insomnia, anxiety and diarrhea or constipation (Lee et al., 2021)." The effects of sleep loss can be measured by absenteeism, decreased worker productivity, and economic costs (Hafner et al., 2017). According to Haffner: "With the evidence on the economic consequences of sleep loss and disorders being limited so far, there is an acute need for systematic analyses of the economic impacts of insufficient sleep, particularly given some evidence of rising rates of insufficient sleep worldwide."

It is apparent from the above discussions that typical studies involving bedroom environmental conditions and sleep quality have focussed on thermal and IAQ, noise and light parameters in a uni-disciplinary approach rather than a preferred multi-disciplinary approach. Factors, such as outdoor air quality, climate, mechanical or natural ventilation, air-conditioning, external and internal noise and light, building typology and occupant behaviour, are not mutually exclusive and are more likely than not to be confounders towards sleep quality in any part of the modern world. Unlike during the awake state in most indoor environments, a person during the sleep state is a "passive participant" who would have no ability to manipulate the bedroom environment.

A vast majority of the people in the tropical belt in countries such as China, India, South Africa and Brazil live in single-family or multifamily dwellings that are naturally ventilated with limited control of their bedroom IEQ, or worse still, without natural or mechanical ventilation. As discussed earlier, an uninformed and less knowledgeable user may not be able to address these confounding effects in an optimal manner. For example, to mitigate external sound transmission into the bedroom, the user may close the windows, an action that would inevitably lead to inadequate ventilation causing thermal discomfort and poor IAQ issues. Such an action could potentially lead to forced use of air-conditioning in certain climates, such as the tropics, that has clear energy implications.

The primary issue is the lack of a holistic approach to IEQ, sleep quality and energy in different types of residential buildings across different climates and socioeconomic realms. This could be further classified as follows:

1. Lack of an integrated assessment of bedroom IEQ and sleep quality
2. Lack of adequate resiliency features in residential buildings to respond to bedroom IEQ in the event of natural or manmade adverse events (wildfires, poor ambient air quality, pandemics)
3. Lack of awareness of IEQ, sleep quality and energy in the global society at large

What does this mean for ASHRAE?

Approximating ideal sleeping conditions is a challenge in real-world situations. Even compromises to approach those conditions are difficult. Tighter housing allows much greater interior environmental control of air movement, noise, temperature, humidity, and filtration, but the skills, knowledge, and understanding of these elements must be combined and approached as a comprehensive system and not fragmented by specialists.

ASHRAE, with an international profile of multidisciplinary technical experts, is uniquely poised to provide guidance on the passive and active design features of bedrooms in residential buildings and their operational performance including the operation and maintenance of heating, ventilating, and air-conditioning systems. The fundamental value ASHRAE can provide through this collaborative effort is to help occupants of diverse socioeconomic status, life stages, and health conditions across the world to obtain optimal sleep quality for their comfort, health, well-being, and productivity.

The *2021 ASHRAE Research Strategic Plan* (ASHRAE 2021) supports moving toward greater involvement in the important area of bedroom environmental quality and sleep quality. For "needed research" the plan calls for:

1. "Development of markers and systems for rating health, comfort and well-being, cognitive performance, and sleep quality."
2. "Identification of relevant pollutants and ventilation requirements—both under normal conditions and during extreme events—based on various criteria that consider health, comfort, cognitive performance, and sleep quality, as well as the requirements for vulnerable groups."

The recommended initiatives in the next section of this document suggest ways of reaching these goals.

The Role of ASHRAE

ASHRAE has the ability to provide guidance and evidence-based information regarding the various factors involved in a restful sleeping environment, thereby increasing the overall health and productivity of occupants and raising awareness of this important topic globally. As a recognized authority for developing standards and guidelines, ASHRAE has demonstrated the capability to evaluate the effectiveness of design measures for new and existing buildings in a systematic manner. ASHRAE, as a leading global HVAC organization, can help improve long-term occupant health and productivity, within the context of a holistic approach to the sleep environment.

Using its well established technical and educational resources, ASHRAE should consider the following actions:

1. Initiate actions to define IEQ in sleeping environments optimal for sleep and revise standards that specifically describe conditions in bedrooms.
2. Support research to evaluate the effectiveness and interactivity of the elements of bedroom IEQ, focusing on enhanced human health and productivity. RBC should coordinate research proposals with appropriate ASHRAE committees and its partner residential organizations
3. Review and develop appropriate carbon-neutral engineering interventions and operational recommendations across different climate zones and socioeconomic realms in both naturally and mechanically ventilated buildings to enhance the bedroom sleeping environment by examining
    - IAQ and ventilation in bedrooms
    - The impact of temperature, noise, and light in bedrooms
    - The interactivity of the elements for healthy IEQ in bedrooms, including
        - Passive/active ventilation and thermal comfort, noise, and light
        - Heating/cooling equipment and ventilation
        - Air filtration and noise
4. Collaborate with other professions and organizations in the bedroom design/sleep quality process. The role of architects and engineers in multifamily dwellings needs to be enhanced in appreciation of the importance of the bedroom IEQ and sleep quality. Additionally, because architects and engineers are less likely to be involved in the design and renovation of single-family, detached dwellings, as compared with multifamily buildings, effective methods must be found to transfer this important knowledge to the single-family housing sector.
5. Modify and evaluate existing, or develop new, ASHRAE Standards and Guidelines to address enhanced occupant health in bedrooms, including possible new requirements in ASHRAE Standard 62.2.
6. Develop a new chapter in *ASHRAE Fundamentals* on this topic, stressing engineering solutions and including the elements of thermal comfort, noise, light, ventilation, and IAQ as they impact sleep quality, long-term health, and productivity.
7. Develop related educational materials for engineering professionals, HVAC technicians, and the public. RBC should coordinate efforts with appropriate ASHRAE committees and its residential partner organizations.

References

Akimoto, M., Sekhar, C., Bivolarova, M. P., Liao, C., Fan, X., Laverge, J., Lan, L., Wargocki, P. 2021. Reviewing how bedroom ventilation affects IAQ and sleep quality. ASHRAE Journal, Vol. 63, Issue 4, pp. 56-60.

Algarni, .S, Khan, R.A., Khan, N.A. *et al.* Particulate matter concentration and health risk assessment for a residential building during COVID-19 pandemic in Abha, Saudi Arabia. *Environ Sci Pollut Res* **28,** 65822–65831 (2021). https://doi.org/10.1007/s11356-021-15534-6

ASHRAE. 2021 ASHRAE Research Strategic Plan. 2021. ASHRAE. https://www.ashrae.org/file%20library/technical%20resources/research/research%20strategic%20plan/research-strategic-plan.pdf

Bartels S, Ögren M, Kim JL, Fredriksson S, Persson Waye K. The impact of nocturnal road traffic noise, bedroom window orientation, and work-related stress on subjective sleep quality: results of a cross-sectional study among working women. Int Arch Occup Environ Health. 2021 Oct;94(7):1523-1536. doi: https://doi.org/10.1007/s00420-021-01696-w. Epub 2021 May 27. PMID: 34043056; PMCID: PMC8384796.

Bernatchez MS, Savard J, Aubin M, Ivers H. Correlates of disrupted sleep-wake variables in patients with advanced cancer. BMJ Support Palliat Care. 2020 Mar;10(1):55-63. doi: https://doi.org/10.1136/bmjspcare-2018-001505. Epub 2018 Jun 30. PMID: 29960955.

Caddick, Zachary A., Kevin Gregory, Lucia Arsintescu, Erin E. Flynn-Evans, A review of the environmental parameters necessary for an optimal sleep environment, Building and Environment, Volume 132, 2018, Pages 11-20, https://doi.org/10.1016/j.buildenv.2018.01.020

Canha, N.; Teixeira, C.; Figueira, M.; Correia, C. How Is Indoor Air Quality during Sleep? A Review of Field Studies. *Atmosphere* **2021**, *12*, 110. https://doi.org/10.3390/atmos12010110

Desaulniers, Jonathan, Sophie Desjardins, Sylvie Lapierre, Alain Desgagné, "Sleep Environment and Insomnia in Elderly Persons Living at Home", *Journal of Aging Research*, vol. 2018, Article ID 8053696, 7 pages, 2018. https://doi.org/10.1155/2018/8053696

Ebben, Matthew R., Peter Yan, Ana C. Krieger, The effects of white noise on sleep and duration in individuals living in a high noise environment in New York City, Sleep Medicine, Volume 83, 2021, Pages 256-259, https://doi.org/10.1016/j.sleep.2021.03.031

Green, A., Dagan, Y. & Haim, A. Exposure to screens of digital media devices, sleep, and concentration abilities in a sample of Israel adults. *Sleep Biol. Rhythms* **16,** 273–281 (2018). https://doi.org/10.1007/s41105-018-0150-1

Hafner, Marco et al. “Why Sleep Matters-The Economic Costs of Insufficient Sleep: A Cross-Country Comparative Analysis.” *Rand health quarterly* vol. 6,4 11. 1 Jan. 2017

Lan, L, Qian, XL, Lian, ZW, Lin, YB. Local body cooling to improve sleep quality and thermal comfort in a hot environment. *Indoor Air*. 2018; 28: 135– 145. https://doi.org/10.1111/ina.12428

Lee DW, Lee J, Kim HR, Kang MY. Health-Related Productivity Loss According to Health Conditions among Workers in South Korea. *Int J Environ Res Public Health*. 2021;18(14):7589. Published 2021 Jul 16. doi:10.3390/ijerph18147589

Liao C, Akimoto M, Bivolarova MP, Sekhar C, Laverge J, Fan X, Lan L, Wargocki P. A survey of bedroom ventilation types and the subjective sleep quality associated with them in Danish housing. Sci Total Environ. 2021 Dec 1;798:149209. https://doi.org/10.1016/j.scitotenv.2021.149209 Epub 2021 Jul 24. PMID: 34332381.

Meng, Qi, Jingwen Zhang, Jian Kang, Yue Wu, Effects of sound environment on the sleep of college students in China, Science of The Total Environment, Volume 70, 2020. https://doi.org/10.1016/j.scitotenv.2019.135794

Mishra, AK, van Ruitenbeek, AM, Loomans, MGLC, Kort, HSM. Window/door opening-mediated bedroom ventilation and its impact on sleep quality of healthy, young adults. *Indoor Air*. 2018; 28: 339– 351. https://doi.org/10.1111/ina.12435

Nassur, Ali-Mohamed, Damien Léger, Marie Lefèvre, Maxime Elbaz, Fanny Mietlicki, Philippe Nguyen, Carlos Ribeiro, Matthieu Sineau, Bernard Laumon, Anne-Sophie Evrard, The impact of aircraft noise exposure on objective parameters of sleep quality: results of the DEBATS study in France. Sleep Medicine, Volume 54,2019, Pages 70-77, https://doi.org/10.1016/j.sleep.2018.10.013

Obayashi K, Yamagami Y, Kurumatani N, Saeki K. Pre-awake light exposure and sleep disturbances: findings from the HEIJO-KYO cohort. Sleep Med. 2019 Feb;54:121-125. https://doi.org/10.1016/j.sleep.2018.10.027. Epub 2018 Nov 14. PMID: 30554055.

Ohayon, Maurice M., Michael C. Chen, Edward Bixler, Yves Dauvilliers, David Gozal, Giuseppe Plazzi, Michael V. Vitiello, Michael Paskow, Anita Roach, Max Hirshkowitz, A provisional tool for the measurement of sleep satisfaction, Sleep Health, Volume 4, Issue 1, 2018, Pages 6-12, https://doi.org/10.1016/j.sleh.2017.11.002

Peters, T. and Halleran, A. (2021), "How our homes impact our health: using a COVID-19 informed approach to examine urban apartment housing", *Archnet-IJAR*, Vol. 15 No. 1, pp. 10-27. https://doi.org/10.1108/ARCH-08-2020-0159

Riedy SM, Smith MG, Rocha S, Basner M. Noise as a sleep aid: A systematic review. Sleep Med Rev. 2021 Feb;55:101385. https://doi.org/10.1016/j.smrv.2020.101385 . Epub 2020 Sep 9. PMID: 33007706.

Röösli, M.; Brink, M.; Rudzik, F.; Cajochen, C.; Ragettli, M.S.; Flückiger, B.; Pieren, R.; Vienneau, D.; Wunderli, J.-M. Associations of Various Night-time Noise Exposure Indicators with Objective Sleep Efficiency and Self-Reported Sleep Quality: A Field Study. *Int. J. Environ. Res. Public Health* **2019**, *16*, 3790. https://doi.org/10.3390/ijerph16203790

Sekhar, Chandra, 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, 2020, https://doi.org/10.1016/j.buildenv.2020.107229

Sekhar, Chandra, Mariya Bivolarova, Mizuho Akimoto & Pawel Wargocki(2021) Detailed characterization of bedroom ventilation during heating season in a naturally ventilated semi-detached house and a mechanically ventilated apartment, Science and Technology for the Built Environment, 27:2, 158-180, DOI: 1080/23744731.2020.1845019

Smith, Michael G., Mikael Ögren, Julia Ageborg Morsing, Kerstin Persson Waye, Effects of ground-borne noise from railway tunnels on sleep: A polysomnographic study. Building and Environment, Volume 149, 2019, Pages 288-296, https://doi.org/10.1016/j.buildenv.2018.12.009

Suni, Eric, Light and sleep. Sleep Foundation, 2020 https://www.sleepfoundation.org/bedroom-environment/light-and-sleep

Veale, D, Ali, S, Papageorgiou, A, Gournay, K. The psychiatric ward environment and nursing observations at night: A qualitative study. *J Psychiatr Ment Health Nurs*. 2020; 27: 342– 351. https://doi.org/10.1111/jpm.12583

Wang, Zihan, Bin Cao, Yingxin Zhu, Questionnaire survey and field investigation on sleep thermal comfort and behavioral adjustments in bedrooms of Chinese residents, Energy and Buildings, Volume 253, 2021, https://doi.org/10.1016/j.enbuild.2021.111462

Contributors

Chandra Sekhar, Ph.D., National University of Singapore, RBC member and Working Group Leader
Gaelle Guyot, Ph.D., Cerema & University of Savoie Mont Blanc (France)
Pawel Wargocki, Ph.D., Technical University of Denmark
Paul Raymer, Heyoka Solutions
Jelle Laverge, Ph.D., Ghent University (Belgium)
Wei Ye, Ph.D., Tongji University, P. R. China
Rick Karg, Residential Energy Dynamics, RBC Chair