Editor's Note: The following columns regarding indoor air quality and occupant productivity appear in the September issues of ASHRAE Journal *and* CIBSE Journal.

Do Indoor CO_2 Levels Directly Affect Perceived Air Quality, Health, or Work Performance?

BY WILLIAM FISK, FELLOW/LIFE MEMBER ASHRAE; PAWEL WARGOCKI, PH.D., ASSOCIATE MEMBER ASHRAE; XIAOJING ZHANG

This article summarizes the findings of 10 recent studies investigating whether increased carbon dioxide (CO_2) concentrations, with other factors constant, influence perceived air quality, health, or work performance of people.

Concentrations of CO_2 in occupied buildings exceed outdoor concentrations because CO_2 is a product of peoples' metabolism. Indoor CO_2 concentrations are indicators of the rates of building ventilation with outdoor air per person. A higher indoor CO_2 concentration is often considered an indicator of poorer indoor air quality (IAQ), although many factors unrelated to indoor CO_2 concentrations influence IAQ. When indoor CO_2 concentrations increase and decrease, concentrations of other indoor air pollutants emitted from indoor sources, particularly the bioeffluents from humans, may also increase and decrease. Increased indoor CO_2 concentrations have often been associated (correlated) with decreases in perceived air quality, with increases in acute health symptoms, and with reductions in aspects of human performance.[1-3] Research prior to 2012, indicated that levels of CO_2 itself, with other conditions constant, had no significant impacts on peoples' health or performance unless the CO_2 concentrations far exceeded the levels found in buildings.[4-10] The occupational limit for CO_2 in the U.S. is 5,000 ppm for a 40 hour workweek.[11] Therefore, the previously documented associations of indoor CO_2 concentrations with perceived air quality, health symptoms, and performance have been attributed to the other indoor air pollutants with changes in concentrations indicated by the changes in indoor concentrations of CO_2.

Since 2012, 10 studies[12–23] have investigated whether increases in moderate CO_2 concentrations, with other conditions constant, adversely influence perceptions of indoor air quality, health, or cognitive performance in humans. The study features are described in Table 5 in the IAQScience website.[24] These studies have been performed with subjects in research facilities enabling CO_2 concentrations to be modified by adding pure CO_2 to indoor air while maintaining all, or nearly all, other conditions constant. By providing high ventilation rates, these studies have maintained low concentrations of bioeffluents. All studies maintained subjects unaware of the CO_2 concentrations. All studies recruited healthy

William Fisk is a senior scientist at Lawrence Berkeley National Laboratory, Berkeley, Calif. Pawel Wargocki, Ph.D., is an associate professor at Technical University of Denmark, Lyngby, Denmark. Xiaojing Zhang is an assistant professor at Beijing University of Technology, Beijing, China.

FIGURE 1 Associations of CO_2 concentrations with cognitive performance.

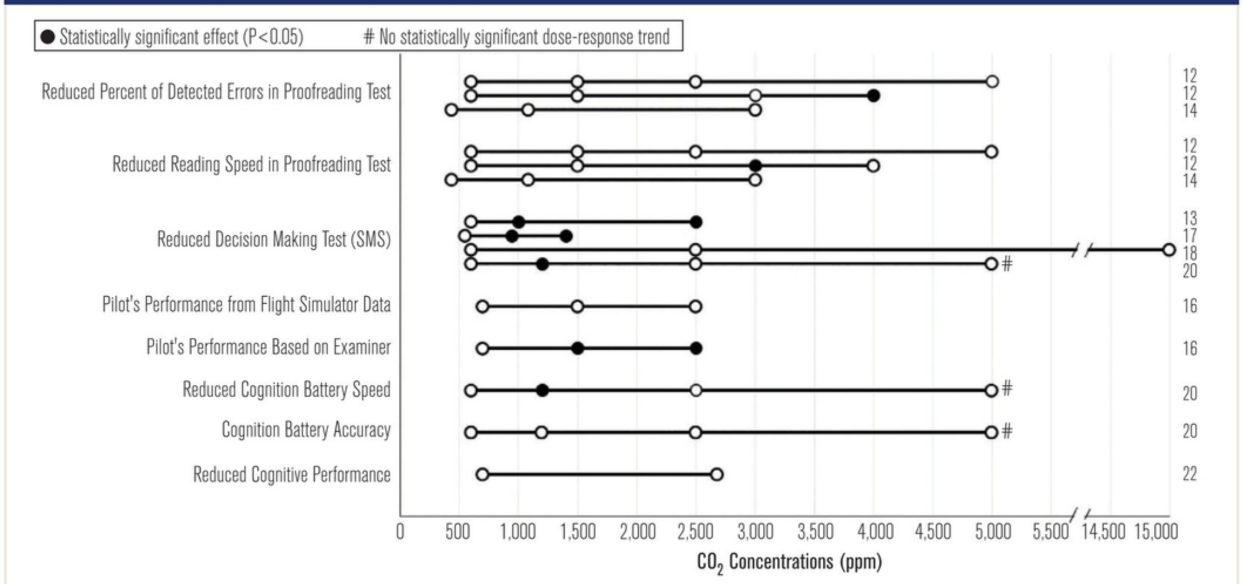
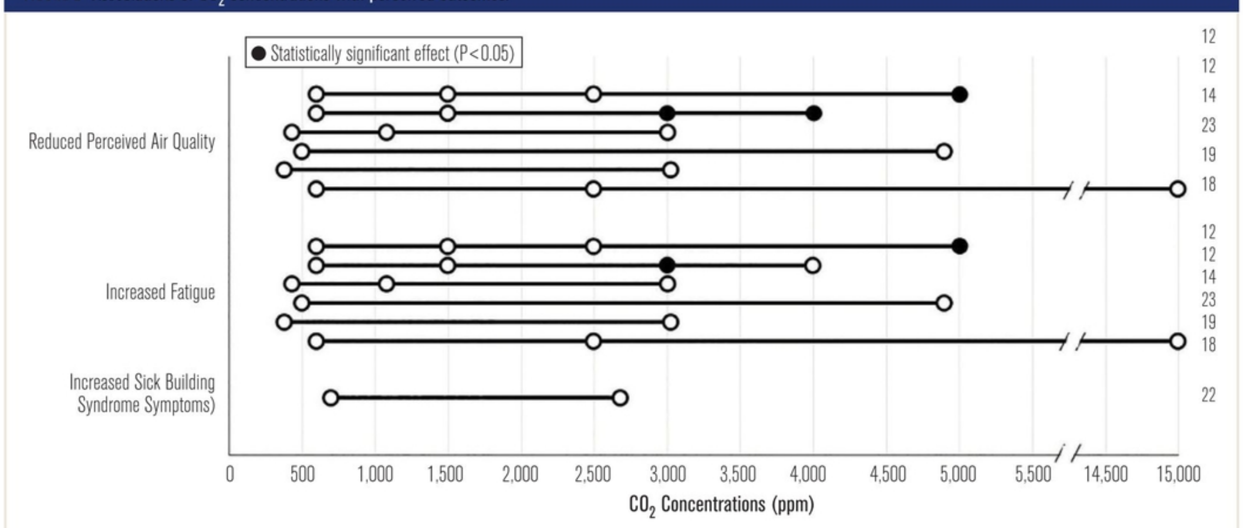


FIGURE 2 Associations of CO_2 concentrations with perceived outcomes.



adults, often college-age adults, as subjects. One study employed pilots[16,21] as subjects, another employed submarine staff,[18] and a third employed staff trained as astronauts.[20] All but one of these studies[18] measured changes in perceptual, health, or performance outcomes for each subject, with each subject exposed to multiple CO_2 concentrations. This design eliminated the potential errors that may occur when comparing different groups of subjects. One study[18] employed a study design with three different groups of subjects, each group exposed to a different level of CO_2 in the indoor air.

Figures 1, 2 and *3* depict the major results of this body of research with each horizontal line representing results from a single study or a part of a study. The circles indicate the CO_2 concentrations employed in the study. A filled in circle indicates a statistically significant (SS) worsening in the outcome at the indicated CO_2 concentration relative to the CO_2 concentration denoted by the leftmost circle. The numbers to the right of each horizontal line indicate the data source.

With respect to subjects' cognitive performance, there are substantial inconsistencies among the results of these experiments. Five studies[12,13,16,17,20] found SS decreases in aspects of cognitive performance, when CO_2 concentrations were increased and, in some instances, the performance decreases were quite substantial in magnitude. Concentrations of CO_2 as low as approximately 1,000 ppm, relative to 500 to 600 ppm, significantly reduced performance.[13,17] Four of these five studies[13,16,17,20] employed demanding tests of cognitive performance, either a 90-minute assessment of decision making via a test system called the strategic management simulation (SMS) or a 180-minute test of pilots' performance in flight simulations. One of these studies[20] found an SS reduction in decision-making performance at 1,200 ppm CO_2 relative to 600 ppm, but performance decreases were not found at 2,500 or 5,000 ppm CO_2. Besides assessing performance in decision-making, this study also employed a battery of more traditional cognitive performance tests and performance in this battery of tests was generally not affected by CO_2 concentrations. The exception was a general trend toward reduced performance with 1,200 ppm CO_2 with the reduction in speed at 1,200 ppm being SS. The fourth study[12] found a SS decrease in performance of a proof reading task but not in other tasks, when CO_2 levels were increased to 3,000 ppm, and proof-reading performance decreased only in one of two experiments. Five additional studies[14,18,19,22,23] found that CO_2 levels had no SS effects on performance. Four of these studies[14,19,22,23] used tests of task performance (e.g., arithmetic tasks, text typing, proof reading, memory) as well as tests of reaction time and attention. In one study,[23] CO_2 levels as high as 5,000 ppm did not influence performance. One of these studies,[19] was conducted at high indoor air temperature of 95°F (35°C) and increased CO_2 did not modify responses attributable to increased temperature. The fourth study[18] found CO_2 levels as high as 15,000 ppm to not affect performance in the SMS test. Overall, among the 10 studies, three[13,16,17] provide strong evidence of reductions in cognitive performance with increased levels of CO_2. Two additional studies[12,20] provide limited evidence of cognitive performance decreases with increased CO_2 levels, but also include

evidence of CO_2 not affecting performance. The results of one additional study,[22] suggest a possible effect of increased CO_2. The mechanism by which increased CO_2 concentrations may affect cognitive performance was not clearly identified in any of the studies. A possible explanation is provided by another study,[25] albeit one that increased CO_2 levels by restricting ventilation rate per person, hence concentrations of other bioeffluents increased when the CO_2 levels were higher. In this study, as subjects were exposed to levels of CO_2 increasing from approximately 400 to 3,000 ppm their forced expiratory volume in 1 second and forced vital capacity decreased. Using models and prior published data, with exposure to higher levels of CO_2, the authors predicted increases in arterial CO_2 partial pressure and corresponding increases in the bicarbonate content of the blood with a reduction in blood pH. The increased blood bicarbonate and reduction in blood pH was suggested as the explanation for a change in brain functioning when occupants are exposed to higher levels of CO_2.

Two papers[15,19] hypothesized that the level of stress associated with the cognitive performance test might explain the discrepancies among findings. Higher CO_2 levels were associated with diminished performance primarily from studies with very demanding, likely stressful, tests of performance. In support of their hypothesis, they found a tendency for subjects to have higher salivary α-amylase concentrations, suggesting higher mental stress, when CO_2 concentrations were increased. Further support for this hypothesis comes from findings that pilots' performance in flight simulations was reduced when their heart rate variability indicated a high level of stress.[21] Also, two studies[12,15] report some increases in blood pressure with exposure to higher CO_2 levels, suggesting higher levels of stress.

The authors of two papers hypothesized that the discrepancies among research findings when subjects took stressful cognitive performance tests was a consequence of the different types of subjects. In one paper,[20] the authors suggested that the astronaut-like operations personnel and submariners might have been better able to compensate for effects of elevated CO_2 due to their

How AJ Manufacturing Helps Make Clean Rooms Clean

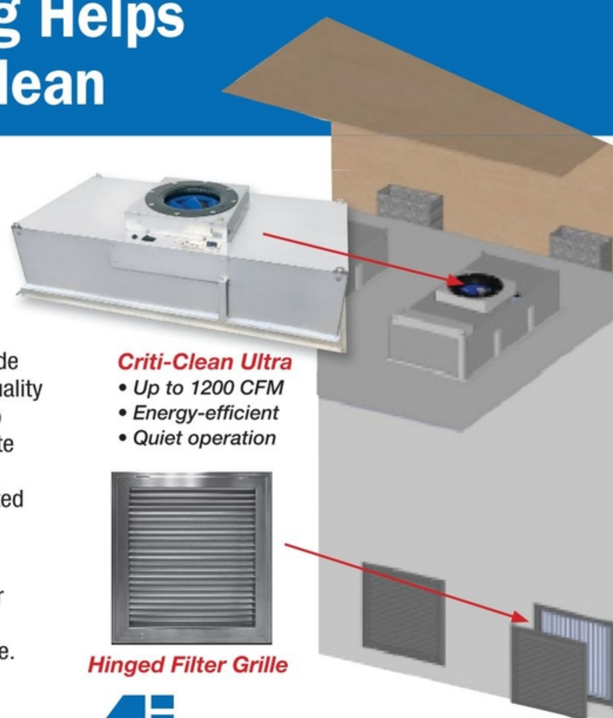
Primary HVAC systems provide conditioned air to a clean room's plenum space, and variable flow exhaust systems maintain the correct room pressure. But it's the stainless steel air distribution products from AJ Manufacturing that help make and keep clean rooms clean, including:

Criti-Clean Ultra FFU

Our Criti-Clean Ultra laminar flow HEPA filter diffusers provide filtered air in a laminar flow over work areas, meeting air quality and room change requirements – including those needed to meet new USP 800 needs in pharmacies. They also eliminate leak paths, allowing IEST 34 Certification. Plus, Criti-Clean Ultra's low plenum height (just 13.7") and available integrated lighting make retrofitting into existing ceiling spaces easier.

Hinged Filter Grilles

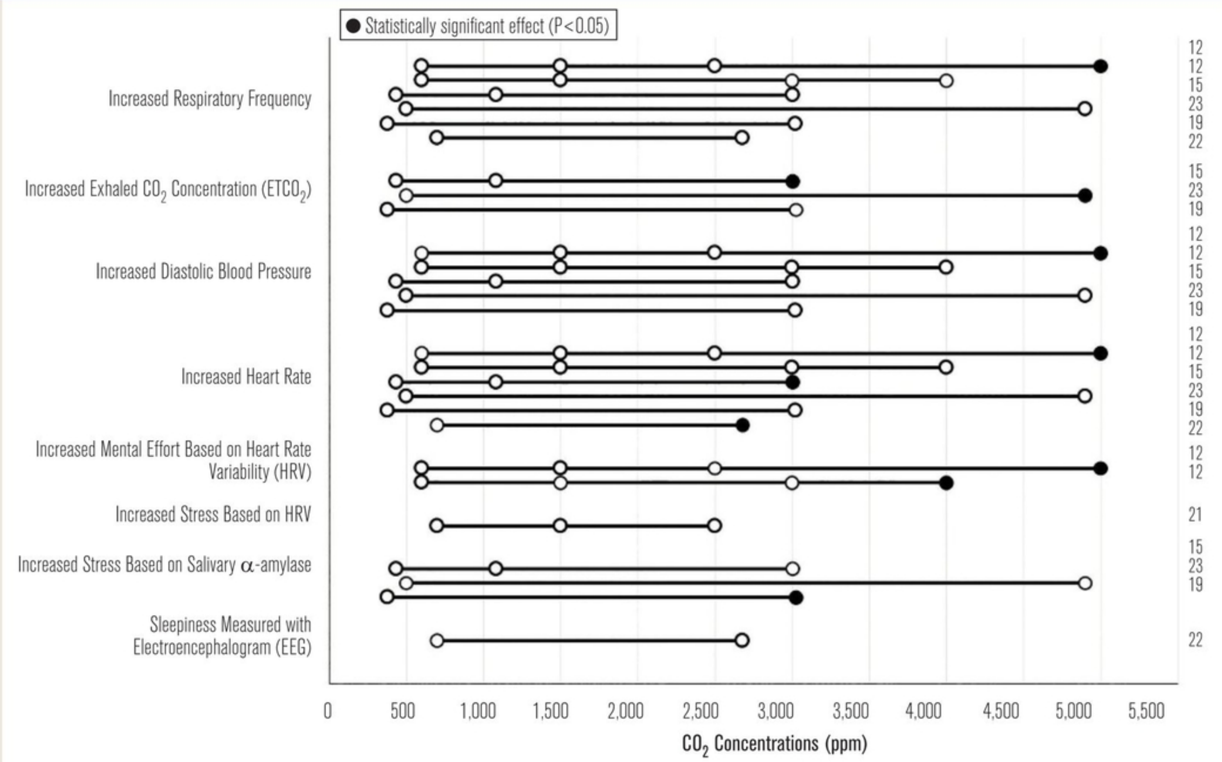
Use our filter grilles as low wall returns to maximize laminar flow in clean room spaces and allow pre-filtering without additional ceiling penetrations to extend HEPA/ULPA filter life.



Need to meet USP 800 pharmacy requirements? Scan code to learn more or contact us today!

AJ MFG. 816-231-5522 ajmfg.com

FIGURE 3 Associations of CO_2 concentrations with physiological outcomes.



prior training. The authors of the other paper[20] hypothesized that their subjects (submariners) might have been unaffected by CO_2 as a consequence of their prior regular occupational exposure to CO_2 at 2,500 ppm or higher concentrations.

Five of the studies[12,14,18,19,23] investigated whether subjects' perceptions of IAQ, e.g., acceptability of indoor air, was influenced by CO_2 concentrations. Only one study[12] found that subjects reported air quality as less acceptable with 3,000 ppm, 4,000 ppm, and 5,000 ppm CO_2 relative to 600 ppm.

Six studies, reported in eight papers,[12,14,15,18,19,21-23] investigated whether the level of CO_2 influenced health symptoms reported on questionnaires or health-related physiological outcomes such as blood pressure, pulse, respiration rate, markers of stress, and exhaled concentrations of CO_2. Four studies that included questionnaires on acute health symptoms,[14,19,22,23] including fatigue, found that CO_2 level had no statistically significant effect on symptoms. One study[12] reported that subjects were significantly more tired with 5,000 ppm CO_2 relative to 600 ppm CO_2. This study[12] also found that blood pressure, respiration rate and volume, and mental effort (based on heart period variability) were increased with higher CO_2 concentrations. In contrast, other studies[15,19,23] generally found no statistically significant effects of CO_2 levels on a broad range of physiological outcomes except for increases in the concentrations of CO_2 in exhaled air, called end-tidal CO_2, and two instances of increases in heart rate. In one study,[15] heart rate decreased less during the exposure session with 3,000 ppm CO_2 vs. 500 ppm CO_2 while another study[22] reported a SS increase in heart rate with exposure to 2,680 ppm CO_2 relative to 700 ppm CO_2. Another study[19] found that levels of α-amylase, markers of mental stress, were higher with 3,000 ppm CO_2 compared to 380 ppm CO_2. Other research[26] has shown that exposure of mice to 2,000 and 4,000 ppm CO_2 for two hours triggers an inflammatory response and vascular injury with generation of microparticles by immune system cells. Also, in human immune system cells, microparticle generation resulted from increased CO_2 exposures.[27]

Main findings of this research are summarized below.

- There is very limited evidence that CO_2 levels below

Can simplicity in kitchen ventilation be taken too far?

We'll let you know.

At Accurex®, we believe working with kitchen ventilation systems should be one of the easiest parts of designing and building commercial kitchens. So we do more than engineer and manufacture advanced, energy-efficient systems. We make it easy for you to specify Accurex products, by simplifying the process, being responsive and getting you information quickly. Discover how simple works, at **ACCUREX.COM**

ACCUREX™
A GREENHECK GROUP COMPANY

© 2019 Accurex, LLC

5,000 ppm influence perceived air quality, acute health symptoms, or physiological outcomes other than end-tidal CO_2 and heart rate. The studies using mice and human immune cells (in vitro) indicate that higher CO_2 levels trigger inflammatory responses, but these findings have not yet been demonstrated in people.

- With respect to acute health symptoms and perceived air quality, the study results, with one exception,[12] are consistent and find no effects at CO_2 below 5,000 ppm.
- The results of research on the effects of moderate CO_2 levels on human cognitive performance are not consistent. Some studies find effects of higher CO_2 concentrations on cognitive performance while other studies find no effects on this outcome.
- There is substantial, but still inconsistent, evidence that performance on challenging tests of decision-making and challenging flight simulations is worsened by CO_2 concentrations as low as 1,000 ppm. The mechanisms underlying the reductions in performance are unknown.
- Further research is needed to address the discrepancies among the current findings. Additionally, research to date has not investigated the effects of CO_2 on children, the elderly, and people with health problems. Also, the effects of long-term continuous or periodic exposures to elevated CO_2 levels has not been investigated. Finally, the extent to which CO_2 mediates the influence of other factors on health or performance requires more research.

References

1. Seppänen, O.A., W.J. Fisk, M.J. Mendell. 1999. "Association of ventilation rates and CO_2 concentrations with health

www.nxtbook.com/nxtbooks/ashrae/ashraejournal_201909/index.php#/78 7/8

and other responses in commercial and institutional buildings." *Indoor Air* 9(4):226–52.

2. Sundell, J., et al. 2011. "Ventilation rates and health: multidisciplinary review of the scientific literature." *Indoor Air* 21(3): 191–204.

3. Fisk , W.J. 2017. "The ventilation problem in schools: literature review." *Indoor Air* 27:1039–1051.

4. Case, E., J. Haldane, 1941. "Human physiology under high pressure: I. Effects of nitrogen, carbon dioxide, and cold." *Journal of Hygiene* 41(3):225–249.

5. Fothergill, D., D. Hedges, J. Morrison. 1991. "Effects of CO_2 and N_2 partial pressures on cognitive and psychomotor performance." Undersea Biomedical Research 18(1):1–19.

6. Vercruyssen, M., E. Kamon, P.A. Hancock. 2007. "Effects of carbon dioxide inhalation on psychomotor and mental performance during exercise and recovery." *International Journal of Occupational Safety and Ergonomics* 13(1):15–27.

7. Sayers, J., et al. 1987. "Effects of carbon dioxide on mental performance." *Journal of Applied Physiology* 63(1): 25–30.

8. Sheehy, J.B., E. Kamon, D. Kiser. 1982. "Effects of carbon dioxide inhalation on psychomotor and mental performance during exercise and recovery." *Human Factors* 24(5):581–588.

9. Henning, R., et al. 1985. "Behavioral impairment with normobaric, hyperoxic 6% CO_2." in Undersea and Hyperbaric Medical Society Annual Scientific Meeting. Long Beach, Calif.

10. Consolazio, W., et al., 1947. "Effects on man of high concentrations of carbon dioxide in relation to various oxygen pressures during exposures as long as 72 hours." *American Journal of Physiology*-Legacy Content. 151(2):479–503.

11. U.S. Department of Labor, Occupational Safety and Health Administration. 2018. Table Z-1 "Limits for air contaminants." [cited 2018 December 7]; Available from: https://www.osha.gov/laws-regs/regulations/standardnumber/1910/1910.1000TABLEZ1.

12. Kajtár, L., L. Herczeg. 2012. "Influence of carbon-dioxide concentration on human well-being and intensity of mental work." *Quarterly Journal of the Hungarian Meteorological Service* 116(2):145–169.

13. Satish, U., et al. 2012. "Is CO_2 an indoor pollutant? Direct effects of low-to-moderate CO_2 concentrations on human decision-making performance." *Environmental Health Perspectives* 120(12):1671–1677.

14. Zhang, X., et al., 2017. "Effects of exposure to carbon dioxide and bioeffluents on perceived air quality, self-assessed acute health symptoms and cognitive performance." *Indoor Air* 27:47–64.

15. Zhang, X.,Wargocki, Z. Lian. 2017. "Physiological responses during exposure to carbon dioxide and bioeffluents at levels typically occurring indoors." *Indoor Air* 27:65–77.

16. Allen, J.G., et al. 2018. "Airplane pilot flight performance on 21 maneuvers in a flight simulator under varying carbon dioxide concentrations." *Journal of Exposure Science & Environmental Epidemiology* https://doi.org/10.1038/s41370-018-0055-8.

17. Allen, J.G., et al. 2016. "Associations of cognitive function scores with carbon dioxide, ventilation, and volatile organic compound exposures in office workers: a controlled exposure study of green and conventional office environments." *Environmental Health Perspectives* (Online). 124(6):805-812.

18. Rodeheffer, C.D., et al. 2018. "Acute exposure to low-to-moderate carbon dioxide levels and submariner decision making." *Aerospace Medicine and Human Performance* 89(6):520–525.

19. Liu, W., W. Zhong, P. Wargocki. 2017. "Performance, acute health symptoms and physiological responses during exposure to high air temperature and carbon dioxide concentration." *Building and Environment* 114:96–105.

20. Scully, R.R., et al. 2019. "Effects of acute exposures to carbon dioxide on decision making and cognition in astronaut-like subjects." npj *Microgravity* 5(1):17.

21. Cao X., et al. 2019. "Heart rate variability and performance of commercial airline pilots during flight simulations." *International Journal of Environmental Research and Public Health* 16:237.

22. Snow, S., et al. 2019. "Exploring the physiological, neurophysiological and cognitive performance effects of elevated carbon dioxide concentrations indoors." *Building and Environment* 156:243-252.

23. Zhang, X.,Wargocki, Z. Lian. 2016. "Human responses to carbon dioxide, a follow-up study at recommended exposure limits in non-industrial environments." *Building and Environment* 100:162–171.

24. Lawrence Berkeley National Laboratory. 2018. "Building ventilation, supporting information." [cited 2018 December 3]; Available from: https://iaqscience.lbl.gov/vent-info.

25. Shriram, S., K. Ramamurthy, S. Ramakrishnan. 2019. "Effect of occupant-induced indoor CO_2 concentration and bioeffluents on human physiology using a spirometric test." *Building and Environment* 149:58–67.

26. Thom, S.R., et al. 2017. "Inflammatory responses to acute elevations of carbon dioxide in mice." *Journal of Applied Physiology* 123(2):297–302.

27. Thom, S.R., et al. 2017. "Increased carbon dioxide levels stimulate neutrophils to produce microparticles and activate the nucleotide-binding domain-like receptor 3 inflammasome." *Free Radical Biology and Medicine* 106:406–416. ■

RAWAL DEVICES, INC

Precision Discharge Air Control with the Rawal APR-E® Valve

Control any single or 2-stage DX system to a precise discharge air setpoint with our electrically driven & electronically controlled **APR-E™**. This Rawal Valve is an external compressor unloader for aftermarket installations. The **APR-E™** provides modulation for any DX air-conditioning system and is easily integrated into an existing BAS/BMS or with a stand-alone controller for New or Retrofit Systems.

OBTAIN THE FLEXIBILITY OF A CHILLED WATER SYSTEM ON A DX BUDGET!

- Dew Point Control for critical environments
- Applicable to any VAV/MUA/DOAS systems
- Reset DAT to minimize reheat for energy savings

RAWAL DEVICES, INC. | PHONE: 800.727.6447
FOR MORE INFORMATION VISIT: WWW.RAWAL.COM
SEND ALL INQUIRIES TO: SALES@RAWAL.COM