

High CO₂ exposure due to facemask wear is unlikely to impair cognition in a warm environment after a long-term adaptation

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Abstract

There is a lack of consensus regarding the impact of indoor CO₂ exposure on cognition. COVID-19 provided an opportunity to study responses to long-term elevated CO₂ exposure from facemask wear. Controlled environmental studies on the possible synergistic effect of warmth and high CO₂ exposure from facemask wear on cognition are rarely reported. We recruited 60 college students to understand whether and the extent facemask wear elevates local CO₂ and impacts cognition at a warm condition. Subjects remained in a controlled summer environmental room (temperature 31.5° C, relative humidity 30%) for 90 min with or without facemasks. Participants completed six cognitive tests and answered surveys using computer-based software. Ten experimental subjects had a second 30 min visit to measure CO₂ concentration at the ala of the nose with and without surgical masks. The results show that wearing a surgical mask sharply increased CO₂ concentration near the nose by 15,000 ppm. Female and male participants had different CO₂ exposure levels by 14-22%. Analysis showed that the experimental group did not exhibit significantly different cognition performance except for short-term memory that was higher instead of lower than the control group. Participants with mask wear showed significantly lower risk-taking, possibly attributed to thermal discomfort. Nevertheless, no significance in cognition or decision making was observed after controlling the familywise error rate using the Bonferroni correction. We hypothesize that the insignificant difference might be caused by adaptation to long-term wear and high CO₂ exposure during COVID-19.

Keywords: Indoor environmental quality; Learning; Thermal comfort; COVID-19; Emotion; Adaptation;

1. Introduction

Exposure to elevated CO₂ indoors is a concern for human health and cognition (Jacobson et al. 2019) and numerous studies on the impacts of indoor CO₂ concentrations on cognition have reported negative findings (B. Du et al. 2020; Satish et al. 2012; Allen et al. 2016; 2019; Cao et al. 2022; Pang et al. 2021). Satish et al. (Satish et al. 2012) showed that concentrations as low as 1,000 ppm impacted cognitive performance and Allen et al. (Allen et al. 2016) found that cognitive performance decreased beginning at concentrations around 945 ppm. Allen et al. (Allen et al. 2019) also found that the flight maneuver passing rate in pilots reduced when exposed to 1,500 ppm compared with 700 ppm. Similarly, Cao et al. (Cao et al. 2022) concluded that indoor CO₂ concentrations as high as 5,000 ppm decreased cognitive function except for short-term memory. Pang et al. (Pang et al. 2021) reported that human vigilance decreased at CO₂ concentrations of 3,500 ppm. Snow et al. (Snow et al. 2019) found that cognitive flexibility and executive function significantly decreased when CO₂ concentrations reached 2,700 ppm. However, this study found no significant variations in reaction times, complex attention, simple attention, sustained attention, or working memory, although concluding a possible lack of learning effect from the elevated CO₂.

However, the results of studies regarding the impacts of indoor CO₂ on cognition are mixed. Rodeheffer et al. (Rodeheffer et al. 2018) and Sculley et al. (Scully et al. 2019) concluded there was no decrease in cognition at higher concentrations. Opposed to the baseline of 600 ppm used in these studies, exposure to CO₂ concentrations of 2,500–15,000 ppm or 2,500–5,000 ppm for submarine and astronaut-like subjects respectively did not decrease cognition. Similarly, Zhang

et. al. (X. Zhang et al. 2017) reported that concentrations as high as 3,000 ppm with pure CO₂ additions had no statistically impactful effects on cognition.

Despite the inconsistency regarding CO₂'s impact on cognition (Jacobson et al. 2019; B. Du et al. 2020; Allen et al. 2016; Satish et al. 2012; Rodeheffer et al. 2018; Cao et al. 2022; Scully et al. 2019; Allen et al. 2019; Pang et al. 2021; X. Zhang et al. 2017; Snow et al. 2019), most studies in the literature examined relatively low CO₂ concentrations (e.g., <3,000 ppm). Due to the COVID-19 pandemic, occupants were encouraged or mandated to wear facemasks to prevent COVID-19 transmission indoors, resulting in exposure to dramatically high CO₂ concentrations. Rhee et al. (Rhee et al. 2021) determined that for a KN95 mask, CO₂ concentrations increased to as high as 24,000–26,000 ppm. Similarly, Roberge et al. (Roberge et al. 2010) examined the physiological impacts of facemask wear on healthcare workers and found the concentration in the dead zone of a respirator to be up to 30,000 ppm. Although the airspace inside of a facemask dilutes the concentration of CO₂ inhaled, the CO₂ exposure for mask wearers is likely close to this high value. Although these high concentrations inside facemasks remain below the NIOSH 15 min exposure limit of 30,000 ppm, this is far above the long-term 8 h limit of 5,000 ppm (NIOSH, n.d.), given that students or office workers were required to wear facemasks almost the whole day. The exceedance of exposure limits could cause concern about how facemask wear impacts human health and cognition.

The period of public facemask mandates during the COVID-19 pandemic (Raifman J et al. 2022) provided the unique opportunity to understand how facemask wear increases locally inhaled CO₂. Facemask mandates also enabled the study of how elevated CO₂ exposure impacts human

cognition and decision-making considering the adaptation to long-term exposure. Reviewing most previous studies in the literature on the impacts of indoor CO₂ exposure, we found that the effect of long-term adaptation has rarely been considered in the experiments and there is a need for studies on the long-term impacts of CO₂ exposure (Jacobson et al. 2019; Persily et al. 2022). Sudden exposure to a relatively high CO₂ in a laboratory chamber may trigger the human body's reaction to a “new” environment, which can be reflected in the performance of cognitive tests.

As mask mandate during COVID-19 created a unique and ephemeral opportunity to make students adapted to daily high CO₂ exposure, three recent studies conducted during COVID-19 investigated the effects of facemask wear on cognition (Tornero-Aguilera and Clemente-Suárez 2021; Smerdon 2022; Schlegtendal et al. 2022). Tornero-Aguilera & Clemente-Suárez (Tornero-Aguilera and Clemente-Suárez 2021) reported that for university students, wearing facemasks during 150 min university lessons did not inhibit cognition compared to students taking online courses without facemasks. Similarly, Schlegtendal et al. (Schlegtendal et al. 2022) found no significant differences in the cognitive performance between students grades five to seven after two school lessons with or without facemasks. Finally, Smerdon (Smerdon 2022) determined that facemasks had minimal impact on cognition for average chess players. However, facemask wear decreased the cognitive performance of expert players, although this was short-lived, and after four hours of play overserved no difference in performance with or without a facemask.

Nevertheless, despite results indicating minimal effects of facemask wear on cognitive performance, these studies were not conducted in a well-controlled thermal environment. Little information was reported regarding other environmental stressors, such as temperature. Recent

studies found that wearing a facemask can increase thermal discomfort (Scarano, Inchingolo, and Lorusso 2020; Tang et al. 2022), especially in warm conditions (R. Zhang et al. 2021; Zhou and Dong 2022; C. Liu et al. 2020). However, these studies do not consider how thermal discomfort from facemask wear impacts cognition. With the increasing frequency, intensity, and duration of heatwaves (Meehl and Tebaldi 2004), occupants might experience both warmness and high CO₂ exposure because of mask wearing, especially in rooms without sufficient air conditioning. Since higher temperatures have been associated with decreases in cognitive function (Taylor et al. 2016; Lan et al. 2022), occupants wearing masks in a warm or hot environment could be subject to dual stressors on cognitive performance and decision-making. Nevertheless, the synergistic effect of both high CO₂ due to facemask wear and thermal discomfort in warm or hot conditions has rarely been investigated. To fill the knowledge gap, this study can shed light on future pandemics or scenarios that expose occupants to both high CO₂ and warmness.

2. Methods

2.1 Participants

We included 60 students from Worcester Polytechnic Institute in our study. We determined the sample size based on previous studies concerning the impact of moderate CO₂ on cognition (Satish et al. 2012). Recruitment was conducted through invitation emails, information flyers, and word of mouth. Subjects were paid \$15/h from when they entered and left the lab. Individuals with colorblindness were excluded from this study as it could interfere with one of the cognitive tests. All subjects who expressed interest were eligible and emailed an informed consent form which they could sign electronically or sign a physical copy before their session. In

addition, subjects were sent a short orientation video with a brief description of the experimental protocol and directed to a signup sheet. Signups were for a single session, limited to one person per session. Experiments were conducted between October 28, 2021, through February 16, 2022. Sessions were made available seven days a week, three separate times during the weekdays and twice on each weekend day. Leading up to the experiment, subjects were reminded by email to be well rested, not to consume caffeine, alcohol, or smoke before their session.

2.2 Randomization and masking

Participants were randomly assigned to the control group without facemasks or the experimental group with facemasks using the Excel RND function. Random number assignments ranged from 1-60, with assignments 1-30 designated to the control group and 31-60 to the experimental. The researchers who contacted participants, assigned the sessions, and carried out the experiment were not involved in the randomization process. Subjects were unaware of the two experimental conditions or their group assignments. To hide subjects from the two groupings, those in the control group were asked to remove their facemask upon entering the chamber while those in the experimental group were instructed to wear a provided surgical mask for the entire experiment. The control group was told that they could remove their facemask since they would be alone in the chamber, while the mask group was instructed to wear a surgical mask to simulate the widespread practice at the time of facemask wear in the classroom. Thus, groups were unaware of the focus of the study on the impacts of facemask wear.

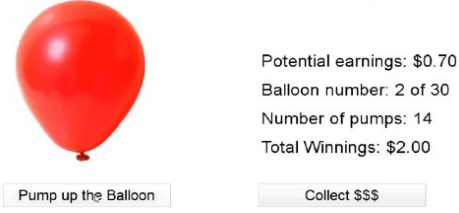
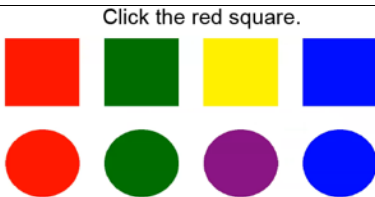
2.3 Environmental Conditions

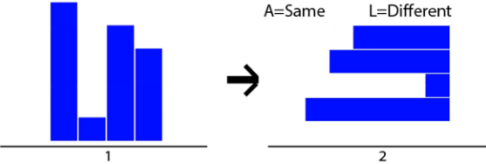
The environmental conditions in the controlled climate chamber were maintained with the temperature at 31.5 ± 0.26 °C (mean $\pm$ standard deviation), relative humidity (RH) at 30 ± 5.30 %, indoor CO₂ at 910 ± 134 ppm, vertical illumination at 303 ± 16 lux, and noise at 63.3 ± 2.69 dB (representing a normal office or classroom with conversation). The indoor temperature was chosen to resemble a worst-case scenario in which mask-wearing may have a stronger influence on cognition and decision-making since warmth can reduce cognitive performance as well, (Wang et al. 2021) especially in buildings where air conditioning (AC) is not sufficient in summer, such as a classroom in the northeastern U.S. during a heatwave. A bottle of water (250 ml) at room temperature was provided.

2.4 Cognition and Decision-Making Tests

To assess cognition and decision-making, each participant completed a series of six tests commonly applied in the literature (Table 1). These included the Balloon Analogue Risk Task (BART) for risk-taking (Lejuez et al. 2002), Token Test assessing working memory (DE RENZI and VIGNOLO 1962), Spatial Processing Test for short-term memory (Englund et al. 1987), AX-Continuous Performance Test (AX-CPT) for attention (Rosvold et al. 1956) Stroop Color Test for response inhibition (Stroop 1935) and Alternative Uses Task for creativity (GUILFORD 1967). The six tests can also measure and/or indicate other cognition as described in Table 1 which displays test descriptions and variables. In particular, our study assessed the impact of mask-wearing associated with high CO₂ exposure on risk-taking behaviors as previous studies have suggested a connection between mask usage and alternations in risk aversion, attitudes, and perception (Xu and Cheng 2021; Wismans et al. 2022; Byrne et al. 2021; Asri et al. 2021; Kaul and Palmer 2022).

Table 1. Cognitive test descriptions and variables. Tests were derived from Millisecond Software LLC and run using Inquisit 6 Version 6.5.1(“Millisecond,” n.d.). BART is primarily used to assess decision-making instead of cognition.

Test	Task Description	Variables	Cognition and decision-making assessed	Graphical user interface
Balloon Analogue Risk Task (BART) (Lejuez et al. 2002)	Participants are given 30 (default) balloons. For each balloon, they get the choice to pump up the balloon or collect their winnings. For each successful pump they can earn one cent. Actual winnings in the BART were added to subject payments to increase incentive.	Average adjusted pump count; Total exploded balloons	Risk taking; Impulsivity; Decision-making under uncertainty.	
Token Test(DE RENZI and VIGNOLO 1962)	Participants are presented rows of rectangles and circles in different colors and are given visual and verbal instructions of what to do with these rectangles and circles (Example: “Click on the red rectangle”). The test has five	Percept accuracy	Working memory; Attention; Executive function; Language comprehension	

	phases (ten trials each) that are progressively more difficult.			
Spatial Processing Test (Englund et al. 1987)	Participants are presented sequentially with two 2, 4, or 6 bar histograms. The first histogram is the target histogram and is always presented in the vertical, upright position. The second histogram is the comparison histogram. It can be rotated clockwise 0-deg, 90-deg, or 180-deg. The task is to decide as fast as possible if the comparison histogram is congruent or incongruent to the target.	Proportion correct; Reaction time	Spatial short-term memory; Spatial working memory; Spatial reasoning; Spatial attention; Spatial perception	
AX Continuous Performance Test (AX-CPT) (Rosvold et al. 1956)	Participants view sequences of letters: cue-distractor-distractor-probe and must decide if the probe is a target (cue = A, probe = X) or not. If the probe is a target, participants press the 'E;' if it's not a target they press the 'I' key.	Proportion correct; reaction time	Sustained and selective attention; Working memory; Cognitive control	

Stroop Color Test (Stroop 1935)	The classic Stroop paradigm demonstrates the interference of word meaning on the naming of the color in which the words are written as measured by reaction time/accuracy differences to color-meaning congruent and color-meaning incongruent combinations.	Proportion correct; Reaction time	Response inhibition; Selective attention. Cognitive flexibility	D=red F=green J=blue K=yellow Green
Alternative Uses Task (AUT) (GUILFORD 1967)	This test has two parts. First, participants are given three everyday objects and are asked to come up with as many creative uses for the current object as possible within 3 min. Afterwards, the computer lists all provided uses for each object and participants are asked to select the top two uses for each. Responses are stored, scored, and assessed by two external independent college students.	Average assessment scores	Creativity; Divergent thinking; Cognitive flexibility;	Write as many creative uses as you can for a brick:  wall weapon

2.5 Surveys

Two surveys presented throughout the experiment assessed emotions and thermal comfort. The Positive and Negative Affect Schedule Short Form (PANAS-SF) (Thompson 2007) assessed emotions, while the ASHRAE 7-point scale (American Society of Heating 1992) was used for thermal evaluation. Visuals and details of the different surveys can be found in Appendix A.1.

Finally, at the conclusion of the study, the experimental group conducted exit interviews. Their response to the question “How do you think the mask impacted your performance?” was recorded by the interviewer.

2.6 Protocol

The experiment was carried out in a Built Environment Research Lab at Worcester Polytechnic Institute in Worcester, Massachusetts, US. Upon arrival, subjects were required to change into provided attire to standardize clothing effects. The ensemble consisted of a cotton short-sleeve t-shirt, athletic shorts, and sneakers, resulting in clothing insulation of 0.36 clo (Tartarini et al. 2020). This was intended to simulate summer attire. After changing, subjects rang a bell to call the experimenter to re-enter the room, and then a short briefing video was played before the experiment began. Then they were asked to wear a provided surgical mask (experimental group) or remove any facemask (control group). Next, participants began a series of six randomly ordered tests and completed surveys through Inquisit 6 (“Millisecond,” n.d.). The total duration of the experiment inside the chamber was 90 min including the 30 min adaptation period (Figure 1). At the end of the experiment, subjects had a brief exit interview.

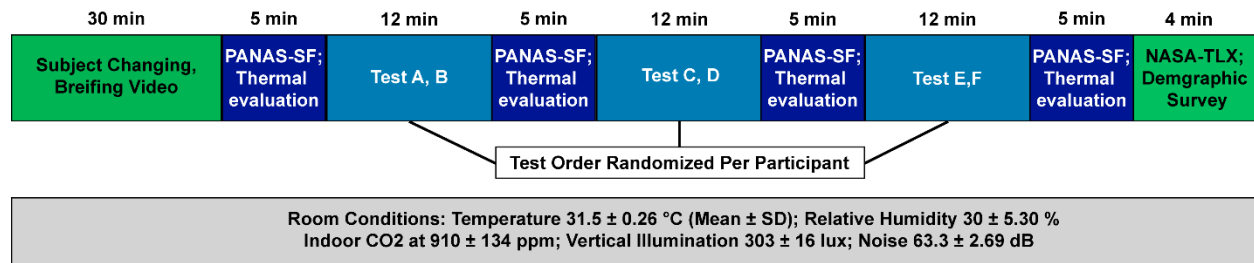


Figure 1. Experimental protocol. Subjects spent 90 min inside the experimental room where they conducted the experiment. After completion, subjects conducted a brief exit interview outside of the room before the end of their visit. (color)

Additionally, to precisely evaluate the increase in CO₂ concentrations due to the surgical mask, we measured the CO₂ concentration at the ala of the nose of ten subjects (five males and five females) with and without mask wear during a second visit. We included equal numbers of both male and female subjects to negate the gender effects of CO₂ generation rates, as male subjects produce higher levels of CO₂ (Yang et al. 2020). Furthermore, by including both male and female participants in the CO₂ measurement, the results will be more representative of the cognition and decision-making experiment that involved both sexes. The sample size was determined based on the CO₂ variation among different participants. More participants did not change the variance significantly. The measurements were taken using a GASLABS CO₂ sensor MS-0001, calibrated by the manufacturer after shipment. The tube connecting the measured air with the sensor was approximately 1 meter in length, without significantly decreasing airflow, with the air pump located before the sensing chamber inside of the device. Data was collected within a 45 min range with a logging interval of 2 s, recording the average concentration over the interval.

For the CO₂ measurement procedure, participants were led into the experimental room, with environmental conditions the same as the original experiment. It consisted of three 10 min windows, the first measuring the CO₂ concentration in the room air, second near the inhale airstream by placing a measuring tube at the ala of the nose without a mask. For the third window, participants were asked to wear a surgical mask and the sensor was placed in the same position as the second window (Figure 2). Measurements were recorded at each condition for 10 min, beginning once the CO₂ concentrations stabilized.



Figure 2. Measurement location for determining CO₂ concentrations of inhaled air at the ala of the nose. (Color)

The research protocol was approved by the Institutional Review Board at Worcester Polytechnic Institute (#20-0001). Funding and support were provided by U.S. National Science Foundation

(#1931077) and Worcester Polytechnic Institute (TRIAD grant). The funders of the study had no role in study design, data collection, analysis, and interpretation, or writing of the report.

2.7 Statistical Analysis

Statistical analysis was conducted with the package (“scipy.stats”) of Python (3.6.9). The Shapiro–Wilk normality test was used to determine whether the data was normally distributed or not, which would decide the further statistical test used for analysis. Differences in cognitive performance, emotions, and thermal evaluation between the two groups were assessed using the Mann-Whitney U Test for nonparametric datasets, and *t*-Test for parametric datasets. The statistical significance was based on $p < 0.05$ (*), $p < 0.01$ (**), and $p < 0.001$ (***). To address the increased risk of type I errors associated with multiple testing, we also employed the Bonferroni correction (Cabin and Mitchell 2000) to control the familywise error rate. The new significant levels were modified by dividing the original significant levels by the number of hypothesis tests. For instance, the new significance level for twelve hypothesis tests was 0.004 (*). By comparing the results using both the regular and Bonferroni-adjusted significance levels, we can determine if a difference remains significant even after considering the increased risk of type I errors due to multiple testing. Further, the effect size of the difference was calculated in terms of Cohen's *d*. (Wassertheil and Cohen 1970). The thresholds of the Cohen's *d* were $|d| < 0.147$ “negligible,” $|d| < 0.33$ “small,” $|d| < 0.474$ “medium,” otherwise “large.”

3. Results

3.1 Subject descriptive data

A total of 60 college students were recruited for and completed this experiment, with five males and five females from the experimental group attending a second visit to measure the CO₂ concentration at the ala of the nose while wearing a surgical mask.

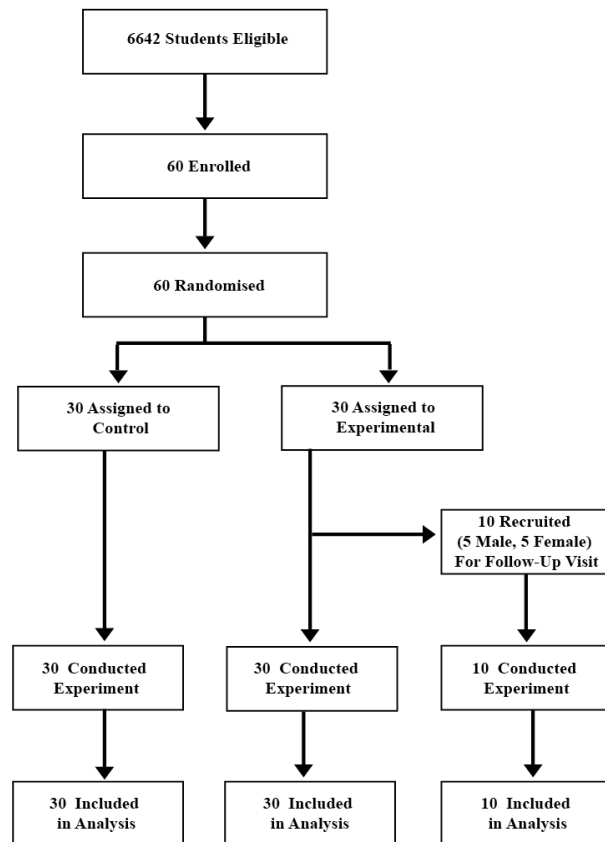


Figure 3. Flowchart of study participation

Subject age, height, and weight were similar between the control and experimental group (Table 2). There was a higher representation of male participants as opposed to females in both the control (66.67% male) and experimental group (63.33% male). Moreover, reported daily physical exercise was higher but without statistical significance for the control group opposed to the experimental group (7.69 (6.54) vs 5.47 (3.90)).

Table 2: Subject Demographics. Results are reported as mean (*SD*) or mean (% group).

		Control	Experimental
Age (years)		20.93 (2.89)	20.93 (2.38)
Sex	Female	10 (33.33%)	11 (36.67%)
	Male	20 (66.67%)	19 (63.33%)
Height (cm)		172.11 (9.55)	168.77 (12.04)
Weight (kg)		69.41 (13.45)	73.29 (18.04)
Exercise (h/week)		7.69 (6.54)	5.47 (3.90)

3.2 CO₂ measurements

We found that the local CO₂ concentration with mask wear was approximately $25,770 \pm 2,318$ that was much higher than 10,770 ppm measured without mask. The results show that even a basic surgical mask can cause an increase in CO₂ exposure at the ala of the nose by almost 15,000 ppm (from 25,770 ppm to 10,770 ppm) compared to the condition without facemask wear.

The measurement also displays a significant fluctuation of CO₂ concentrations that can be attributed to tidal breathing. Female participants experienced a higher exposure to CO₂ by 22% than the male counterparts without a mask but a lower exposure by 14% when wearing a mask, partly attributing to both metabolism and the tightness of mask wearing. The structures of the thermal plume near the breathing zone might also contribute to the observed discrepancies that require further investigation. In addition, our findings also confirmed that surgical masks raise CO₂ concentrations at the ala of the nose to a level over 25,000 ppm as observed similarly in the

study with a KN95 mask (Rhee et al. 2021). As a result, assessing the participants' cognitive decline when exposed to such high CO₂ concentrations will help investigate whether a relatively moderate level of exposure (e.g., 1,000 ppm (Allen et al. 2016; Satish et al. 2012), 5,000 ppm (Cao et al. 2022)) can impair cognition in buildings. Specifically, if cognitive performance remains unaffected at high CO₂ concentrations, it is unlikely to be negatively impacted at lower CO₂ levels either. We will delve into the cognitive findings in the following section.

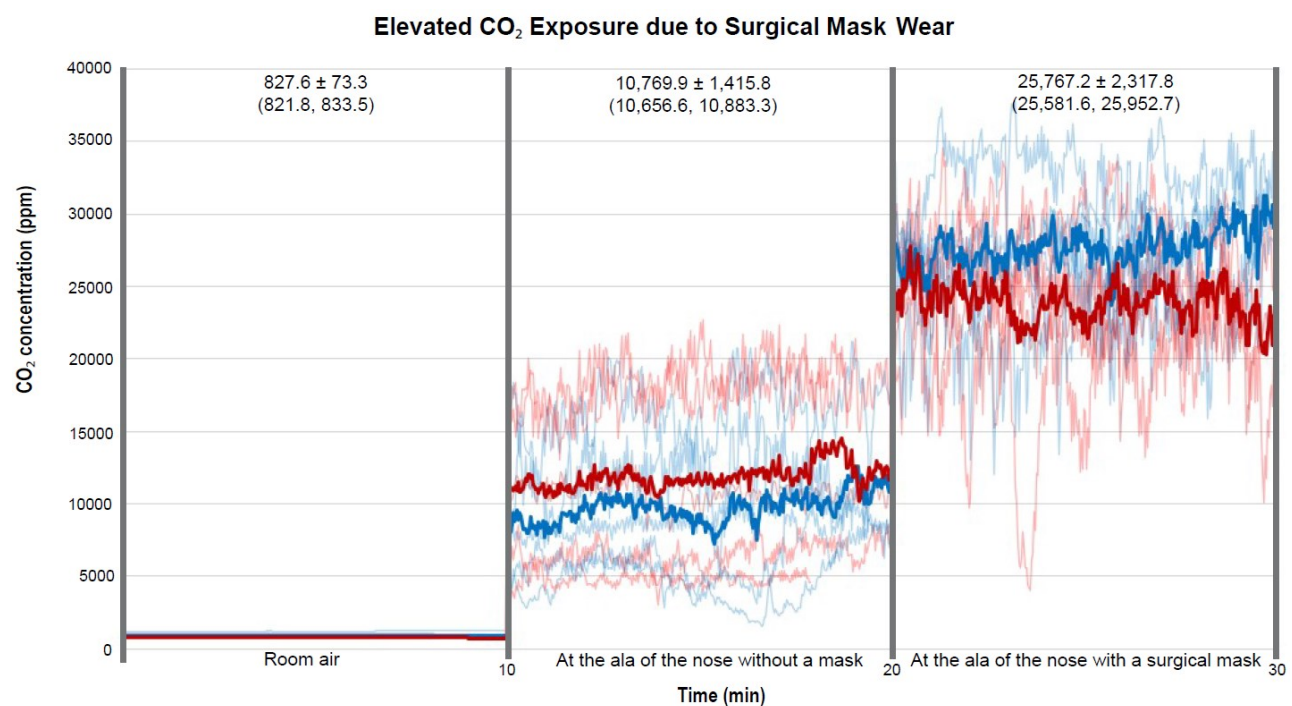


Figure 4. Increase in local CO₂ concentration due to mask wear. Measuring the concentration of CO₂ at the ala of the nose with and without a surgical facemask. CO₂ concentrations for male subjects are displayed in faint blue, with bold blue as the male average. Female subject concentrations and averages are in red and bold red, respectively. The mean±SD (95% CI) for each condition is displayed at the top of each section. (color)

3.3 Cognitive test data

Between the control and experimental groups, of the six cognitive tests, only risk-taking, and short-term memory showed slightly significant differences. The total number of exploded balloons of the BART was higher for the experimental group ($p=0.047$, 9.93 (SD 4.06) vs 12.13 (4.33)). For short-term memory, the experimental group that wore facemasks performed better instead of worse on the spatial processing task for the proportion correct of histograms rotated at 0 degrees ($p=0.037$, 0.55 (0.17) vs 0.47 (0.12)). However, the difference in either risk-taking or short-term memory was significant only at the regular significance level (0.05) but did not meet the stricter criterion based on the Bonferroni-adjusted significant level ($0.05/12=0.004$). The results imply weaker evidence to reject the null hypothesis that there is no significant difference between the control and experimental groups for the two tests.

Table 3. Results for six cognitive tests. Performance on the six cognitive tests between groups. Results are reported as mean (SD). * Denotes $p<0.05$.

Test		Cognition	Control	Experimental	P -value	Cohen's d
		or				
		Decision -				
		Making				
Percent	Token Test	Working	92.50	93.20	0.47	-0.19
Accuracy		Memory	(3.70)	(3.36)		
Total	BART	Risk	12.13	9.93	0.047*	0.524
Explosions		Taking	(4.33)	(4.06)		

Average	BART	Risk	42.19	38.50	0.30	0.268
Adjusted Pump Count		Taking	(13.41)	(14.15)		
Proportion Correct	AX-CPT	Attention	0.90 (0.23)	0.90 (0.19)	0.37	-0.03
Reaction Time (ms)	AX-CPT	Attention	444.96 (103.02)	452.57 (143.49)	0.47	-0.061
Proportion Correct	Stroop Color Test	Response Inhibition	0.95 (0.04)	0.96 (0.04)	0.39	-0.23
Reaction Time (ms)	Stroop Color Test	Response Inhibition	928.09 (216.67)	892.69 (116.97)	0.51	0.17
Proportion Correct 0-deg	Spatial Processing	Short Term Memory	0.47 (0.17)	0.55 (0.12)	0.037*	-0.55
Proportion Correct 90-deg	Spatial Processing	Short Term Memory	0.80 (0.13)	0.79 (0.16)	0.46	0.038
Proportion Correct 180-deg	Spatial Processing	Short Term Memory	0.43 (0.15)	0.42 (0.17)	0.69	0.11
Reaction Time (ms)	Spatial Processing	Short Term Memory	1316.0 (279.81)	1278.69 (727.64)	0.60	0.14
Creativity score	Alternate Uses Task	Creativity	3.20 (0.91)	3.35 (0.83)	0.51	-0.17

3.4 Survey data

For the PANAS-SF, and thermal evaluation survey showed no significant differences in responses between the two groups.

Table 4. Results for PANAS-SF and thermal evaluations.

	Survey	Control	Experimental	<i>P</i> -value	Cohen's <i>d</i>
Positive Emotions	PANAS-SF	3.01 (0.95)	3.27 (0.87)	0.28	0.28
Negative Emotions	PANAS-SF	1.31 (0.35)	1.27 (0.37)	0.20	-0.11
Thermal Comfort	Thermal Evaluation	-0.33 (4.21)	-0.83 (3.75)	0.60	0.13
Thermal Sensation	Thermal Evaluation	4.02 (2.20)	4.20 (2.25)	0.48	-0.082
Thermal Acceptability	Thermal Evaluation	0.95 (4.30)	0.66 (4.16)	0.71	0.069
Thermal Preference	Thermal Evaluation	-3.45 (3.45)	-4.24 (2.73)	0.11	0.25

Moreover, exit interview responses were gathered from twenty-four participants in the experimental group. Responses for subject numbers 31, 57, 58, 59, and 60 were not recorded due to experimenter error. Exit interview responses can be found in the Appendix A.2.

4. Discussion

In our study involving 60 university students, our findings suggest that even in a warm learning environment, surgical facemask wear does not negatively impact most measures of cognition even though this increased local CO₂ concentrations by 15,000 ppm. We found the exception of reduced risk-taking in the control group versus the experimental group with fewer total exploded balloons within the experimental group. Although performance for short-term memory differed between the two groups, the experimental group's performance was better than the control.

Although the difference in risk-taking was not significant after the Bonferroni correction, the higher overall thermal dissatisfaction of the experimental group could be an explanation. BART was the only test not on a set timer or intended to be done quickly. Due to being more thermally uncomfortable, although not statistically significant, the group wearing facemasks would try to finish the task quicker to exit the warm environment sooner. The elevated temperature in the experimental room was outside of the comfort zones established by ASHRAE (American Society of Heating 1992). Based on the thermal evaluation between groups, both groups were thermally uncomfortable, hot thermal sensation, and preferred the environment to be cooler. However, the experimental group had a higher magnitude rating on these measures, and reported lower thermal acceptability, indicating that the facemasks intensified negative thermal evaluations in the high-temperature environment.

The exit interview responses moreover support the higher thermal discomfort due to facemask wear. Of the nine subjects who expressed negative perceptions of facemask wear, six of these

exclusively expressed discomfort only due to the elevated temperature environment making the mask physically uncomfortable.

Despite local CO₂ concentrations reaching upwards to approximately 25,000 ppm combined with the warm environment, the cognitive performance of students wearing a facemask regarding working and short-term memory, attention, response inhibition, and creativity was not negatively impacted, even without controlling the familywise error rate using the Bonferroni correction. A potential explanation for these results includes long-term adaptation effects owing to the mask mandate. Physiological studies supporting long-term adaptations have primarily been limited to temperature adaptations (C. Du et al. 2018; Ning, Wang, and Ji 2016; VANOIJEN et al. 2004). However, studies on facemask wear and cognition during the pandemic showed that long-term adaptation to mask wear led to minimal impacts of facemask wear on cognition (Tornero-Aguilera and Clemente-Suárez 2021; Smerdon 2022; Schlegtendal et al. 2022). Adaptations to elevated local CO₂ concentrations have also been supported by Rodeheffer et al. (Rodeheffer et al. 2018) who concluded that military submarine workers' cognition showed no statistical difference among three CO₂ levels (600, 2500, or 15,000 ppm), attributing to possible adaptation mechanisms.

Support for adaptive behaviors to mask-wearing was provided by the exit interviews conducted at the end of our study. To understand sentiments towards facemask wear not captured by tests or surveys, subjects who wore facemasks were asked at the conclusion of the experiment "How do you think the mask impacted your performance?" Responses were collected from twenty-four subjects, with fifteen subjects expressing minimal impacts of the mask. Of these fifteen, eight

specifically referenced that they had adapted to wearing facemasks, so participants in this study likely adapted to mask-wearing during COVID-19. Our experiment was conducted during facemask mandates when students wore facemasks during class and in-person meetings throughout the entire workday for months. Despite intermittent breaks in wear, such as while eating, drinking, or being outside, we estimated that the average exposure level to CO₂ during a class day exceeded the 8 h NIOSH exposure limit of 5,000 ppm for students on campus.

Although our study suggests that local CO₂ concentrations of up to 25,000 due to facemask wear may not be a concern for a healthy student population or impact cognition, it is important to note potential consequences of physiological changes due to mask-wearing and elevated CO₂. Many studies on CO₂ focus on relatively low concentrations (e.g., <3,000 ppm), however one study by Maniscalco et al. (Maniscalco et al. 2022) found that subjects exposed to CO₂ as high as 20,000 ppm experienced no adverse health effects, even though subjects were cycling in these conditions. This supports our study findings by suggesting that the high concentrations experienced with facemask wear less likely lead to adverse health effects. Additional studies on the physiological impacts of facemask wear reported that blood oxygen saturation did not reach levels associated with cognition and mental fatigue and remained within the normal range of 95%-98% (Beder et al. 2008; Tornero-Aguilera and Clemente-Suárez 2021).

As with any experiment, our results are limited to the setting and population. We reduced threats to the generalizability of the results by creating an experimental setting that simulated warm summer days in the Northeast Region of the United States. The participants in our study were recruited from the student population who were healthy enough to attend school. To extend the

generalizability of results to populations other than participants in our study future research is needed. There is evidence that physiological changes associated with mask wear can be particularly crucial for at-risk populations. For example, one study focusing on pregnant women during the pandemic observed that due to the low-ventilated space created by facemasks participants' hemoglobin levels were significantly higher although still within normal levels for pregnant women (Friedrich et al. 2021). Changes in hemoglobin levels (e.g., anemia), are shown to cause problems in cognition, mood, and basic activity in elderly populations (Lucca et al. 2008). Therefore, further studies on the physiological impacts of high CO₂ exposure on at-risk populations are needed.

Moreover, the sample size in this study might be relatively small to conclusively determine the effect of high CO₂ exposure on cognition and decision-making, even though the sample size of 60 participants in this study was larger than those in some previous studies as described in Table 5. To address this concern, we conducted a post-hoc power analysis using G*Power 3.1.9.7 (Faul et al. 2007) based on 0.55, the largest effect size obtained from the experiment. The analysis yielded an achieved power of 0.66, which is lower than the conventional threshold of 0.8. This finding suggests that a larger sample size may be required to obtain results with higher confidence. Hence, we strongly recommend a larger sample size on this topic for future studies.

Table 5. Sample size in studies investigated the impact of CO₂ on cognition

Author, Year	Number of Participants	Experimental Design
Satish et al., 2012 [3]	22	Within-subjects

Allen et al. 2016 [4]	24	Within-subjects
Zhang et al. 2016 (Xiaojing Zhang, Wargocki, and Lian 2016)	10	Within-subjects
Zhang et al. 2017 (X. Zhang et al. 2017)	25	Within-subjects
Liu et al. 2017 (W. Liu, Zhong, and Wargocki 2017)	12	Within-subjects
Rodeheffer et al. 2018 (Rodeheffer et al. 2018)	36	Between-subjects
Scully et al. 2019 (Scully et al. 2019)	22	Within-subjects
Snow et al. 2019 (Snow et al. 2019)	31	Within-Subjects
Pang et al. 2021 (Pang et al. 2021)	15	Within-subject
Cao et al. 2022 (Cao et al. 2022)	15	Within-subjects
This study	60	Between-subjects

5. Conclusion

This study aims to find evidence to determine whether high-level CO₂ exposure can negatively impact cognition and decision-making. We discovered that mask-wearing during COVID-19 can increase the CO₂ concentration near the nose to approximately 25,000 ppm, corresponding to a 15,000 ppm increase in CO₂ concentration at the ala of the nose from the baseline of without a mask in the experiment.

Such an increase due to mask-wearing was considerably higher than a low or moderate level, such as 1,500 ppm of indoor CO₂, which had been reported to impair cognition in previous studies. However, our laboratory experiments even in a warm environment with 60 participants using a between-subjects design suggest that exposure to 25,000 ppm CO₂ does not generally cause a significant reduction in cognition. The only exception is the exploded balloon count of the Balloon Analogue Risk Task assessing risk taking as a component of decision-making. Moreover, this exception might be attributed to the fact that participants felt thermally uncomfortable while wearing a facemask, leading them to pump the balloon fewer times. On the contrary, participants exposed to high CO₂ due to facemask wear demonstrated even better performance in spatial processing tasks. However, after applying the Bonferroni adjustment for significance levels, none of the tests resulted in significant differences in cognition, decision-making or emotions between the two groups. We hypothesize that mask mandates on campus during COVID-19 enabled long-term adaptation to high CO₂ exposure for the participants.

Therefore, we conclude that high CO₂ exposure due to facemask wear is very unlikely to cause a significant reduction in cognition or decision-making. Our results provide more evidence in examining the effect of high CO₂ exposure on cognition and decision-making by considering

long-term adaptation. Nevertheless, we exercise caution in acknowledging that conclusions are drawn from this study. Studies involving human subjects should be corroborated through further investigations considering different environmental settings and tackling this contentious topic from various perspectives. We also recommend that future studies, preferably with large sample sizes, consider the effects of long-term adaptation, which has not been incorporated into the mechanism but may serve as a moderating factor.

CRedit authorship contribution statement

RH Conceptualization, Methodology, Software, Formal Analysis, Investigation, Writing – Original Draft, Review and Editing, Visualization **MB** Methodology, Software, Validation, Formal Analysis, Investigation **SD** Conceptualization, Methodology, Writing – Review and Editing **SS** Conceptualization, Methodology, Writing – Review and Editing **GS** Conceptualization, Methodology, Writing – Review and Editing **SL**: Conceptualization, Methodology, Resources, Writing – Review and Editing, Supervision, Project Administration, Funding Acquisition **HZ** Writing – Editing and Reviewing **JZ** Writing – Editing and Reviewing

Declaration of Competing of Interest

To the authors' knowledge, there is no conflict of interest.

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Data Sharing

The data is available on open framework

https://osf.io/3nqr7/view_only=ef25bac188f24af58eaffd8767be3532

References

- Allen, Joseph G., Piers MacNaughton, Jose Guillermo Cedeno-Laurent, Xiaodong Cao, Skye Flanigan, Jose Vallarino, Francisco Rueda, Deborah Donnelly-McLay, and John D. Spengler. 2019. "Airplane Pilot Flight Performance on 21 Maneuvers in a Flight Simulator under Varying Carbon Dioxide Concentrations." *Journal of Exposure Science & Environmental Epidemiology* 29 (4): 457–68. <https://doi.org/10.1038/s41370-018-0055-8>.
- Allen, Joseph G., Piers MacNaughton, Usha Satish, Suresh Santanam, Jose Vallarino, and John D. Spengler. 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* 124 (6): 805–12. <https://doi.org/10.1289/ehp.1510037>.
- American Society of Heating, Refrigerating and Air-Conditioning Engineers. 1992. "ASHRAE Standard Thermal Environmental Conditions for Human Occupancy." Atlanta.
- Asri, Ankush, Viola Asri, Baiba Renerte, Franziska Föllmi-Heusi, Joerg D. Leuppi, Juergen Muser, Reto Nüesch, Dominik Schuler, and Urs Fischbacher. 2021. "Wearing a Mask—For Yourself or for Others? Behavioral Correlates of Mask Wearing among COVID-19 Frontline Workers." *PLOS ONE* 16 (7): e0253621. <https://doi.org/10.1371/journal.pone.0253621>.
- Beder, A., Ü. Büyükköçak, H. Sabuncuoğlu, Z.A. Keskil, and S. Keskil. 2008. "Preliminary Report on Surgical Mask Induced Deoxygenation during Major Surgery." *Neurocirugía* 19 (2): 121–26. [https://doi.org/10.1016/S1130-1473\(08\)70235-5](https://doi.org/10.1016/S1130-1473(08)70235-5).
- Byrne, Kaileigh A., Stephanie G. Six, Reza Ghaiumy Anaraky, Maggie W. Harris, and Emma L. Winterlind. 2021. "Risk-Taking Unmasked: Using Risky Choice and Temporal Discounting to Explain COVID-19 Preventative Behaviors." *PLOS ONE* 16 (5): e0251073. <https://doi.org/10.1371/journal.pone.0251073>.
- Cabin, R J, and R J Mitchell. 2000. "To Bonferroni or Not to Bonferroni: When and How Are the Questions." *Bulletin of the Ecological Society of America* 81 (3).
- Cao, Xiaodong, Pei Li, Jie Zhang, and Liping Pang. 2022. "Associations of Human Cognitive Abilities with Elevated Carbon Dioxide Concentrations in an Enclosed Chamber." *Atmosphere* 13 (6): 891. <https://doi.org/10.3390/atmos13060891>.
- Du, Bowen, Marlie C. Tandoc, Michael L. Mack, and Jeffrey A. Siegel. 2020. "Indoor CO₂ Concentrations and Cognitive Function: A Critical Review." *Indoor Air* 30 (6): 1067–82. <https://doi.org/10.1111/ina.12706>.
- Du, Chenqiu, Baizhan Li, Yong Cheng, Chao Li, Hong Liu, and Runming Yao. 2018. "Influence of Human Thermal Adaptation and Its Development on Human Thermal Responses to Warm Environments." *Building and Environment* 139 (July): 134–45. <https://doi.org/10.1016/j.buildenv.2018.05.025>.
- Englund, C, D Reeves, Clark Shingledecker, and D Thorne. 1987. "Unified Tri-Service Cognitive Performance Assessment Battery (UTC-PAB). 1. Design and Specification of the Battery." San Diego California.

- Faul, Franz, Edgar Erdfelder, Albert-Georg Lang, and Axel Buchner. 2007. "G*Power 3: A Flexible Statistical Power Analysis Program for the Social, Behavioral, and Biomedical Sciences." *Behavior Research Methods* 39 (2): 175–91. <https://doi.org/10.3758/BF03193146>.
- Friedrich, Lior, Gabriel Levin, Nitzan Maixner, Yossi Bart, Abraham Tsur, Yoav Yinon, and Raanan Meyer. 2021. "Hematologic Adaptation to Mask-wearing among Pregnant Women and Obstetrical Outcome during the Coronavirus Disease 2019 Pandemic." *International Journal of Gynecology & Obstetrics* 154 (2): 297–303. <https://doi.org/10.1002/ijgo.13715>.
- GUILFORD, J. P. 1967. "Creativity: Yesterday, Today and Tomorrow." *The Journal of Creative Behavior* 1 (1): 3–14. <https://doi.org/10.1002/j.2162-6057.1967.tb00002.x>.
- Jacobson, Tyler A., Jasdeep S. Kler, Michael T. Hernke, Rudolf K. Braun, Keith C. Meyer, and William E. Funk. 2019. "Direct Human Health Risks of Increased Atmospheric Carbon Dioxide." *Nature Sustainability* 2 (8): 691–701. <https://doi.org/10.1038/s41893-019-0323-1>.
- Kaul, Vasundhara, and Zachary D. Palmer. 2022. "'You Are Responsible for Your Own Safety': An Intersectional Analysis of Mask-Wearing During the COVID-19 Pandemic." *Social Currents*. <https://doi.org/10.1177/23294965221145904>.
- Lan, Li, Jieyu Tang, Pawel Wargocki, David P Wyon, and Zhiwei Lian. 2022. "Cognitive Performance Was Reduced by Higher Air Temperature Even When Thermal Comfort Was Maintained over the 24–28°C Range." *Indoor Air* 32 (1). <https://doi.org/10.1111/ina.12916>.
- Lejuez, C. W., Jennifer P. Read, Christopher W. Kahler, Jerry B. Richards, Susan E. Ramsey, Gregory L. Stuart, David R. Strong, and Richard A. Brown. 2002. "Evaluation of a Behavioral Measure of Risk Taking: The Balloon Analogue Risk Task (BART)." *Journal of Experimental Psychology: Applied* 8 (2): 75–84. <https://doi.org/10.1037/1076-898X.8.2.75>.
- Liu, Cong, Guojian Li, Yuhang He, Zixuan Zhang, and Yujian Ding. 2020. "Effects of Wearing Masks on Human Health and Comfort during the COVID-19 Pandemic." *IOP Conference Series: Earth and Environmental Science* 531 (1): 012034. <https://doi.org/10.1088/1755-1315/531/1/012034>.
- Liu, Weiwei, Weidi Zhong, and Pawel Wargocki. 2017. "Performance, Acute Health Symptoms and Physiological Responses during Exposure to High Air Temperature and Carbon Dioxide Concentration." *Building and Environment* 114. <https://doi.org/10.1016/j.buildenv.2016.12.020>.
- Lucca, Ugo, Mauro Tettamanti, Paola Mosconi, Giovanni Apolone, Francesca Gandini, Alessandro Nobili, Maria Vittoria Tallone, et al. 2008. "Association of Mild Anemia with Cognitive, Functional, Mood and Quality of Life Outcomes in the Elderly: The 'Health and Anemia' Study." *PLoS ONE* 3 (4): e1920. <https://doi.org/10.1371/journal.pone.0001920>.
- Maniscalco, Janin, Frank Hoffmeyer, Christian Monsé, Birger Jettkant, Eike Marek, Thomas Brüning, Jürgen Bünger, and Kirsten Sucker. 2022. "Physiological Responses, Self-reported Health Effects, and Cognitive Performance during Exposure to Carbon Dioxide at 20 000 Ppm." *Indoor Air* 32 (1). <https://doi.org/10.1111/ina.12939>.
- Meehl, Gerald A., and Claudia Tebaldi. 2004. "More Intense, More Frequent, and Longer Lasting Heat Waves in the 21st Century." *Science* 305 (5686): 994–97. <https://doi.org/10.1126/science.1098704>.
- "Millisecond." n.d.

- Ning, Haoran, Zhaojun Wang, and Yuchen Ji. 2016. “Thermal History and Adaptation: Does a Long-Term Indoor Thermal Exposure Impact Human Thermal Adaptability?” *Applied Energy* 183 (December): 22–30. <https://doi.org/10.1016/j.apenergy.2016.08.157>.
- NIOSH. n.d. “Occupational Exposure Limits.” Center for Disease Control and Prevention.
- Pang, Liping, Jie Zhang, Xiaodong Cao, Xin Wang, Jin Liang, Liang Zhang, and Liang Guo. 2021. “The Effects of Carbon Dioxide Exposure Concentrations on Human Vigilance and Sentiment in an Enclosed Workplace Environment.” *Indoor Air* 31 (2). <https://doi.org/10.1111/ina.12746>.
- Persily, Andrew, William Bahnfleth, Howard Kipen, Josephine Lau, Corinne Mandin, Chandra Sekhar, Pawel Wargocki, and Lan Chi Nguyen Weekes. 2022. “ASHRAE Position Document on Indoor Carbon Dioxide.” *American Society of Heating, Refrigerating, Air-Conditioning Engineers Inc.* Atlanta, Georgia.
- Raifman J, Nocka K, Jones D, Bor J, Lipson S, and Chan P. 2022. “Face Mask Mandates.” COVID-19 US State Policy Database. April 1, 2022. <https://statepolicies.com/data/graphs/face-masks/>.
- RENZI, E. DE, and L. A. VIGNOLO. 1962. “THE TOKEN TEST: A SENSITIVE TEST TO DETECT RECEPTIVE DISTURBANCES IN APHASICS.” *Brain* 85 (4): 665–78. <https://doi.org/10.1093/brain/85.4.665>.
- Rhee, Michelle S. M., Carin D. Lindquist, Matthew T. Silvestrini, Amanda C. Chan, Jonathan J. Y. Ong, and Vijay K. Sharma. 2021. “Carbon Dioxide Increases with Face Masks but Remains below Short-Term NIOSH Limits.” *BMC Infectious Diseases* 21 (1): 354. <https://doi.org/10.1186/s12879-021-06056-0>.
- Roberge, Raymond J, Aitor Coca, W Jon Williams, Jeffrey B Powell, and Andrew J Palmiero. 2010. “Physiological Impact of the N95 Filtering Facepiece Respirator on Healthcare Workers.” *Respiratory Care* 55 (5): 569–77.
- Rodeheffer, Christopher D., Sarah Chabal, John M. Clarke, and David M. Fothergill. 2018. “Acute Exposure to Low-to-Moderate Carbon Dioxide Levels and Submariner Decision Making.” *Aerospace Medicine and Human Performance* 89 (6): 520–25. <https://doi.org/10.3357/AMHP.5010.2018>.
- Rosvold, H. Enger, Allan F. Mirsky, Irwin Sarason, Edwin D. Bransome, and Lloyd H. Beck. 1956. “A Continuous Performance Test of Brain Damage.” *Journal of Consulting Psychology* 20 (5): 343–50. <https://doi.org/10.1037/h0043220>.
- Satish, Usha, Mark J. Mendell, Krishnamurthy Shekhar, Toshifumi Hotchi, Douglas Sullivan, Siegfried Streufert, and William J. Fisk. 2012. “Is CO₂ an Indoor Pollutant? Direct Effects of Low-to-Moderate CO₂ Concentrations on Human Decision-Making Performance.” *Environmental Health Perspectives* 120 (12): 1671–77. <https://doi.org/10.1289/ehp.1104789>.
- Scarano, Antonio, Francesco Inchingolo, and Felice Lorusso. 2020. “Facial Skin Temperature and Discomfort When Wearing Protective Face Masks: Thermal Infrared Imaging Evaluation and Hands Moving the Mask.” *International Journal of Environmental Research and Public Health* 17 (13): 4624. <https://doi.org/10.3390/ijerph17134624>.
- Schlegtendal, Anne, Lynn Eitner, Michael Falkenstein, Anna Hoffmann, Thomas Lücke, Kathrin Sinnigen, and Folke Brinkmann. 2022. “To Mask or Not to Mask—Evaluation of Cognitive

- Performance in Children Wearing Face Masks during School Lessons (MasKids).” *Children* 9 (1): 95. <https://doi.org/10.3390/children9010095>.
- Scully, Robert R., Mathias Basner, Jad Nasrini, Chiu-wing Lam, Emanuel Hermosillo, Ruben C. Gur, Tyler Moore, David J. Alexander, Usha Satish, and Valerie E. Ryder. 2019. “Effects of Acute Exposures to Carbon Dioxide on Decision Making and Cognition in Astronaut-like Subjects.” *Npj Microgravity* 5 (1): 17. <https://doi.org/10.1038/s41526-019-0071-6>.
- Smerdon, David. 2022. “The Effect of Masks on Cognitive Performance.” *Proceedings of the National Academy of Sciences* 119 (49). <https://doi.org/10.1073/pnas.2206528119>.
- Snow, Stephen, Amy S. Boyson, Karlien H.W. Paas, Hannah Gough, Marco Felipe King, Janet Barlow, Catherine J. Noakes, and M. C. schraefel. 2019. “Exploring the Physiological, Neurophysiological and Cognitive Performance Effects of Elevated Carbon Dioxide Concentrations Indoors.” *Building and Environment* 156. <https://doi.org/10.1016/j.buildenv.2019.04.010>.
- Stroop, J. R. 1935. “Studies of Interference in Serial Verbal Reactions.” *Journal of Experimental Psychology* 18 (6): 643–62. <https://doi.org/10.1037/h0054651>.
- Tang, Tianwei, Yongcheng Zhu, Xiaoqing Zhou, Zhisheng Guo, Yudong Mao, Huilin Jiang, Zhaosong Fang, Zhimin Zheng, and Xiaohui Chen. 2022. “Investigation of the Effects of Face Masks on Thermal Comfort in Guangzhou, China.” *Building and Environment* 214 (April): 108932. <https://doi.org/10.1016/j.buildenv.2022.108932>.
- Tartarini, Federico, Stefano Schiavon, Toby Cheung, and Tyler Hoyt. 2020. “CBE Thermal Comfort Tool: Online Tool for Thermal Comfort Calculations and Visualizations.” *SoftwareX* 12 (July): 100563. <https://doi.org/10.1016/j.softx.2020.100563>.
- Taylor, Lee, Samuel L. Watkins, Hannah Marshall, Ben J. Dascombe, and Josh Foster. 2016. “The Impact of Different Environmental Conditions on Cognitive Function: A Focused Review.” *Frontiers in Physiology*. <https://doi.org/10.3389/fphys.2015.00372>.
- Thompson, Edmund R. 2007. “Development and Validation of an Internationally Reliable Short-Form of the Positive and Negative Affect Schedule (PANAS).” *Journal of Cross-Cultural Psychology* 38 (2): 227–42. <https://doi.org/10.1177/0022022106297301>.
- Tornero-Aguilera, José Francisco, and Vicente Javier Clemente-Suárez. 2021. “Cognitive and Psychophysiological Impact of Surgical Mask Use during University Lessons.” *Physiology and Behavior* 234. <https://doi.org/10.1016/j.physbeh.2021.113342>.
- VANOOIJEN, A, W VANMARKENLICHTENBELT, A VANSTEENHOVEN, and K WESTERTERP. 2004. “Seasonal Changes in Metabolic and Temperature Responses to Cold Air in Humans.” *Physiology & Behavior* 82 (2–3): 545–53. <https://doi.org/10.1016/j.physbeh.2004.05.001>.
- Wang, Chao, Fan Zhang, Julian Wang, James K. Doyle, Peter A. Hancock, Cheuk Ming Mak, and Shichao Liu. 2021. “How Indoor Environmental Quality Affects Occupants’ Cognitive Functions: A Systematic Review.” *Building and Environment*. <https://doi.org/10.1016/j.buildenv.2021.107647>.
- Wassertheil, Sylvia, and Jacob Cohen. 1970. “Statistical Power Analysis for the Behavioral Sciences.” *Biometrics* 26 (3). <https://doi.org/10.2307/2529115>.

- Wismans, Annelot, Peter van der Zwan, Karl Wennberg, Ingmar Franken, Jinia Mukerjee, Rui Baptista, Jorge Barrientos Marín, et al. 2022. “Face Mask Use during the COVID-19 Pandemic: How Risk Perception, Experience with COVID-19, and Attitude towards Government Interact with Country-Wide Policy Stringency.” *BMC Public Health* 22 (1). <https://doi.org/10.1186/s12889-022-13632-9>.
- Xu, Ping, and Jiuqing Cheng. 2021. “Individual Differences in Social Distancing and Mask-Wearing in the Pandemic of COVID-19: The Role of Need for Cognition, Self-Control and Risk Attitude.” *Personality and Individual Differences* 175 (June): 110706. <https://doi.org/10.1016/j.paid.2021.110706>.
- Yang, Liu, Xueni Wang, Minghui Li, Xiang Zhou, Shichao Liu, Hui Zhang, Edward Arens, and Yongchao Zhai. 2020. “Carbon Dioxide Generation Rates of Different Age and Gender under Various Activity Levels.” *Building and Environment* 186. <https://doi.org/10.1016/j.buildenv.2020.107317>.
- Zhang, Ruhang, Jianhua Liu, Liang Zhang, Jindi Lin, and Qingqing Wu. 2021. “The Distorted Power of Medical Surgical Masks for Changing the Human Thermal Psychology of Indoor Personnel in Summer.” *Indoor Air* 31 (5): 1645–56. <https://doi.org/10.1111/ina.12830>.
- Zhang, X., P. Wargocki, Z. Lian, and C. Thyregod. 2017. “Effects of Exposure to Carbon Dioxide and Bioeffluents on Perceived Air Quality, Self-Assessed Acute Health Symptoms, and Cognitive Performance.” *Indoor Air* 27 (1): 47–64. <https://doi.org/10.1111/ina.12284>.
- Zhang, Xiaojing, Pawel Wargocki, and Zhiwei Lian. 2016. “Human Responses to Carbon Dioxide, a Follow-up Study at Recommended Exposure Limits in Non-Industrial Environments.” *Building and Environment* 100 (May): 162–71. <https://doi.org/10.1016/j.buildenv.2016.02.014>.
- Zhou, Zhiqiang, and Liang Dong. 2022. “Experimental Investigation of the Effect of Surgical Masks on Outdoor Thermal Comfort in Xiamen, China.” *Building and Environment*, December, 109893. <https://doi.org/10.1016/j.buildenv.2022.109893>.