Topic: Health and Indoor Air Quality/Covid-19, Pandemics, and Epidemics

Do We Overestimate the Impact of Carbon Dioxide on Cognition and Decision-Making?: Preliminary Evidence

Rachel, F. Hurley[1], Mohamed A. Belyamani[1], Soussan Djamasbi[2], Gbetonmasse B. Somasse[3], Sarah Strauss[4], Shichao Liu[1]

[1]Department of Civil, Environmental, and Architectural Engineering, Worcester Polytechnic Institute, Worcester, MA
[2]School of Business, Worcester Polytechnic Institute, Worcester, MA
[3]Department of Social Science and Policy Studies, Worcester Polytechnic Institute, Worcester, MA
[4]Department of Integrative and Global Studies, Worcester Polytechnic Institute, Worcester, MA

[*]*Corresponding email: rhurley@wpi.edu*

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SUMMARY

The purpose of this study is to investigate the combined impact of mask-wearing on cognitive performance and risk-taking behaviors. Participants were divided into a control group (N=24) without and an experimental group (N=27) with a surgical mask. Both groups completed the tasks in a warm environment (30 ºC) where the conditions can reduce cognition and decision-making as well. These conditions are common in indoor spaces without sufficient air conditioning during a heat wave. Cognition and risk-taking behaviors were assessed using computerized tests. Results showed that mask-wearing in warm environment did not negatively impact cognitive performance, nor did it increase risk-taking behavior as the concept of risk compensation predicts, even when the CO_2 concentration was elevated to approximately 29,000 ppm on average inside the mask. On the contrary, mask-wearing participants showed less risk-taking behaviors, slightly better response inhibition and better short-term memory. These results do not support previous findings suggesting that even a moderately increased indoor CO_2 level can reduce cognition. We hypothesize that human adaptation effects (due to mask-wearing on a daily basis) make people less vulnerable to the adverse environment (i.e., excessive air temperature and CO_2 levels), which will be investigated in the future studies.

INTRODUCTION

With the ongoing pandemic, mask mandates and daily wear in school and office environments have become the norm. There have been studies on elevated CO_2 levels (even 24,000 – 26,000 ppm for a KN95 mask [1]) for inhaled air when wearing a mask. The CO_2 level inside the mask is outrageously high for the widely-accepted "norm" in the field of building science. The assertion that even a moderate-level (~1,000 ppm) indoor CO_2 can be detrimental to cognition was made in a prominent study by Satish et al [2] at Lawrence Berkeley National Laboratory (LBNL).

Collaborating with the leading author of the LBNL study [2], Allen et al. [3] corroborated the results in the experimental lab of Syracuse University a few years later. The possible mechanism is that high CO_2 exposure can reduce blood oxygen saturation that is related to impaired cognition [4]. Also, wearing a mask might be associated with risk-taking behaviors due to risk compensation [5]. Due to COVID-19, mask wearing is likely to be part of many people's daily routine, including at work or in school. Therefore, it is important to examine how mask wearing can impact cognition and risk-taking behaviors. Furthermore, since warm environments may also contribute to reduced cognition [6], it is worthy to investigate the combined effects of elevated CO_2 and air temperature on cognition.

METHODS

This study was conducted at Worcester Polytechnic Institute during the COVID-19 pandemic when the mask mandate was in effect. Fifty-one participants in the experiment were randomly assigned to the control group (*N=24* without a mask) or experimental group (*N=27* with a surgical mask). All participants reported that they had been wearing a mask for months or more than one year due to the university policy requiring all students to wear a mask (or other facial covering) on campus. The participants consisted of slightly more male students who could have a higher CO_2 generation rate than females (Table 1) [7].

Table 1. Anthropometric data for the participants in the two groups

Group	**Female**	**Male**	**Age** *Mean (SD) [median]*	**Height (cm)** *Mean (SD) [median]*	**Weight (kg)** *Mean (SD) [median]*	**Exercise time (hr/week)** *Mean (SD) [median]*
Control *(n=24)*	9	15	20.4 (4.7) [19.5]	174.1 (9.0) [176.9]	71.2 (12.5) [69.2]	8.8 (6.5) [7.0]
Mask-wearing *(n=27)*	12	15	20.7 (2.4) [20.0]	168.8 (12.0) [172.0]	72.5 (18.5) [66.0]	5.4 (4.0) [5.0]

Note: *no significant difference was found between the two groups in terms of the metrics.*

Each participant completed the *Balloon Analogue Risk Task (BART)* [8] and five cognitive tests, namely, the *Token Test* for working memory [9], *Spatial Processing Test* [10] for short-term memory, *AX-Continuous Performance Test (AX-CPT)* for attention [11], *Stroop Color Test* for response inhibition [10], and *Alternative Uses Task* for creativity [12]. Cognitive loads were assessed using NASA-TLX [13]. All tests and NASA-TLX were administered on Inquisit (Milisecond Software, LLC). Table 2 describes them in more detail.

The environmental conditions in the controlled climate chamber were maintained with the temperature at 30 Cognt, relative humidity (RH) at 40%, indoor CO_2 at 800 ppm, vertical illumination at 300 lux, and noise at 60 dB (representing a normal office or classroom with conversation). The indoor temperature (30 °C) was chosen to resemble a worst-case scenario in which mask-wearing may have a stronger influence on cognition and decision making since warmness can reduce cognitive performance [6], especially in buildings where air conditioning (AC) is not sufficient in summer, such as a classroom without AC in the northeastern U.S. during a heatwave. The clothing insulation was approximately 0.36 clo, resulting in a predicted mean vote (PMV), 1.25 (slightly warm sensation) [14]. Subjects were seated at a table and conducted computerized tasks. A bottle of water (250 ml) was provided at the room temperature.

The study applied thvere design of a between-subject experiment. Each participant had only one visit to complete all tests and questionnaires, in order to reduce the learning effects as demonstrated by cognitive tests. During the visit, a participant spent 30 min in the chamber for thermal adaptation and then completed questionnaires and cognitive tests as detailed in Figure 1. The total duration of the entire experiment was about 80 minutes.

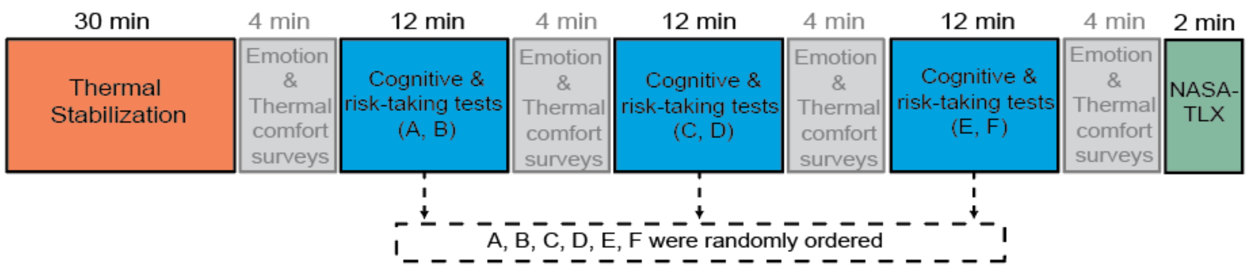

Figure 1. Experimental protocol for all participants. A-F represents the five cognitive tests and the Balloon Analogue Risk Task (BART) test [8].

The statistical analysis was conducted with the package ("scipy.stats") of Python (3.6.9). The normality of the datasets in each group was tested using the Shapiro–Wilk normality test. Then the differences in emotions and cognition between the two groups were assessed using the *Mann-Whitney U Test* for nonparametric datasets, and *t-Test* for parametric datasets. Also, the effect size of the difference was calculated in terms of Cohen's d [15]. The thresholds of the Cohen's d were $|d| < 0.147$ "negligible", $|d| < 0.33$ "small", $|d| < 0.474$ "medium", otherwise "large". The statistical significance was based on $p < 0.05$ (*), $p < 0.01$(**), and $p < 0.001$ (***).

RESULTS AND DISCUSSION

Figure 2 shows the CO_2 concentrations inside the surgical mask for one female and one male participant. The CO_2 levels can reach approximately 29,000 ppm during 15 min that is around 14-folder higher than that without a mask (~2,000 ppm) near the nasolabial fold. If we hypothetically assume that people's CO_2 generation rate does not change greatly with indoor CO_2 level, wearing a surgical mask is equivalent to an elevation of 27,000 ppm in the indoor air CO_2 level.

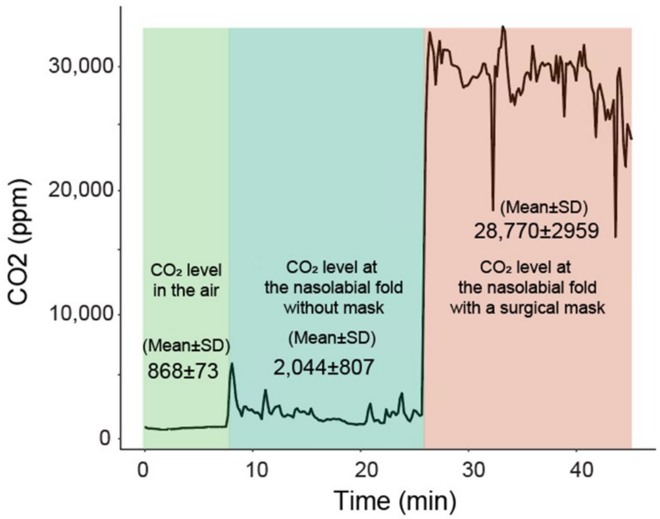

Figure 2. CO_2 levels in the air and at the nasolabial fold with and without a surgical mask for a participant. The CO_2 level with a mask is comparable to a recent study [1].

Despite being exposed to such a high CO_2 level, mask-wearing participants did not perform poorly on the cognitive tests relative to the control group participants, who did not wear a mask. On the contrary, the mask-wearing group demonstrated even better cognitive performance for some tests. *Table 1* describes the statistical summary of the performance of five cognitive tests and cognitive load. There is no statistically significant difference found based on ($p<0.05$) between the two groups for all cognitive metrics except for *"total explosions"* for risk-taking behaviors, *"proportion correct"* for response inhibition, and *"proportion correct (0-deg)"* for short-term memory. One reason might be that blood oxygen saturation is still in the normal range of 90%-98% even with a mask [16]. Another major reason is the adaptation effects after continuous wear of masks since the start of the pandemic. Instead of adversely affecting cognition, however, mask-wearing is associated with participants' less risk-taking, increased response inhibition, and promoted short-term memory.

Table 1. Statistical summary of the cognitive performance between the two groups

Cognitive test or load	**Metric**	**Mean (SD) [Median]**		**P-value**		
		Control group (N= 24)	***Experiment group (N=27)***	***Mann Whitney***	***t-Test***	***Cohen's d***
Working Memory (Token Test) [5]	Percent accuracy	92.8 (3.79) [93.00]	93.6 (3.13) [94.00]	0.171	NA	-0.233
Risk-Taking (BART) [8]	Total explosions	12.7 (4.35) [12]	9.8 (4.24) [9]	NA	**0.019***	0.683
	Average adjusted pump count^{+}	44.0 (14.05) [42.97]	37.8 (14.54) [35.41]	NA	0.129	0.433
Attention (AX-CPT) [11]	Proportion correct	0.88 (0.260) [0.980]	0.90 (0.197) [0.980]	0.360	NA	-0.081
	Reaction time (ms)	415.5 (74.59) [402.60]	458.7 (149.80) [420.50]	0.123	NA	-0.367

Response Inhibition (Stroop Color Test) [10]	Proportion correct	0.95 (0.036) [0.940]	0.96 (0.042) [0.964]	**0.049***	NA	-0.384
	Reaction time (ms)	917.0 (222.30) [865.00]	896.1 (172.20) [887.20]	0.489	NA	0.106
Short Term Memory (Spatial Processing) [18]	Proportion correct (0-deg)	0.46 (0.171) [0.470]	0.55 (0.121) [0.556]	NA	**0.043***	-0.589
	Proportion correct (90-deg)	0.79 (0.132) [0.780]	0.80 (0.144) [0.789]	0.407	NA	-0.079
	Proportion correct (180-deg)	0.42 (0.154) [0.415]	0.41 (0.151) [0.375]	0.367	NA	0.114
	Reaction time (ms)	1262 (277.7) [1294.0]	1286 (261.4) [1264.0]	NA	0.754	-0.089
NASA TLX [19]	Task load	0.69 (2.80) [1.58]	0.91 (2.333) [0.833]	NA	0.992	0.086

$^{+}$ *The "average adjusted pump count" refers to pumps used for unpopped balloons.*
Please note that the results of the Alternative Uses Task are not shown here since the evaluation of participants' inputs relies on authors' subjective assessments.

In order to further understand the possible detriments of mask-wearing on cognition and emotion, we had a short interview with the participants at the end of the session. Sixteen of the twenty-seven participants (59.3%) in the mask-wearing group indicated no whatsoever effects of mask-wearing on cognition or emotion or thermal comfort, because they have adapted to wearing a mask. Many of them were not aware of mask-wearing at all. However, ten participants (37.0%) reported negative impact to some extent. In particular, six of them were aware of mask-wearing due to the warm room temperature and reported elevated thermal discomfort. Two subjects mentioned that mask-wearing adversely impacted their performance of the cognitive tests, but the impact was mainly associated with thermal discomfort. Furthermore, please note that participants only had one visit (either with or without a mask), and as such their feedback on mask-wearing's effects on cognition and emotions may represent a general perception beyond what had been shaped during the visit.

The study had 51 healthy college students and therefore the results might not be generalized to other populations, such as people with asthma. In addition, future research is needed to understand the role of adaptation in the effects of the indoor environment on cognition.

CONCLUSIONS

Wearing a surgical mask can substantially increase the CO_2 level to approximately 29,000 ppm. In this study, we investigated whether such a high CO_2 concentration could significantly impact cognitive performance and risk-taking behaviors through a between-subject experiment with 51 student participants. To magnify the potentially adverse impact of mask-wearing, this study exposed participants to a warm environment (30 ^{o}C) representing an unconditioned space during a heatwave. Contrary to the indicated effects of elevated CO_2 levels in the literature in the field of building science, this study finds no significantly worse cognitive performance for participants wearing a surgical mask as compared with their counterparts without a mask. The evidence does not support the surging concern that even a moderate-level CO_2 indoors can deteriorate cognition. The underlying hypothesized mechanism of adaptation needs further investigation.

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