Fossil fuel combustion is driving indoor CO_2 toward levels harmful to human cognition

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Abstract

Human activities are elevating atmospheric carbon dioxide concentrations to levels unprecedented in human history. The majority of anticipated impacts of anthropogenic CO_2 emissions are mediated by climate warming. Recent experimental studies in the fields of indoor air quality and cognitive psychology and neuroscience, however, have revealed significant direct effects of indoor CO_2 levels on cognitive function. Here we shed light on this connection, and estimate the impact of continued fossil fuel emissions on human cognition. We conclude that indoor CO_2 levels may indeed reach levels harmful to cognition by the end of this century, and the best way to prevent this hidden consequence of climate change is to reduce fossil fuel emissions. Finally, we offer recommendations for a broad, interdisciplinary approach to improving such understanding and prediction.

Key Points

- Atmospheric carbon dioxide concentrations are reaching levels never experienced by *Homo Sapiens*.
- Recent experiments have linked high indoor carbon dioxide concentrations to reduced cognitive function.
- Our models predict that future carbon emissions will increase indoor concentrations to levels harmful to human cognition.

Main Text

The vast majority of the impacts of anthropogenic climate change on human health and society are *indirect* to the forcing, *e.g.*, increased mortality due to more frequent heatwaves is an expected outcome, but humans are not directly adding heat to the atmosphere. Modern human activity emits greenhouse gases, which raise the near–surface air temperature via the greenhouse effect and make heatwaves more probable (Stott *et al.* 2004; Gasparrini *et al.* 2017). Consider the loss of habitat due to sea level rise. The forcing—again, increasing concentrations of greenhouse gases such as carbon dioxide (CO_2) in the atmosphere—causes seawater to warm and thus expand, and glaciers and ice sheets to melt into the sea, both of which increase the volume of the ocean such that coastlines retreat and low–lying islands are at least partially submerged (Church *et al.* 2013). Indeed, most of the perceptible impacts of climate change are linked indirectly to the underlying forcing, with atmospheric warming playing a prominent role along the chain of causality.

But not *all* impacts are brokered by warming or other intermediate responses of the climate system to greenhouse gas emissions. In fact, oceanographers have long stressed that even if technologies are developed and deployed that prevent Earth's surface temperature from increasing despite rapidly growing CO_2 emissions (*e.g.*, geoengineering proposals such as solar radiation management), CO_2 itself has a direct and extremely dangerous impact on marine ecosystems. Carbon dioxide entering the surface ocean undergoes a chemical reaction to raise the acidity (lower the pH) of seawater and ultimately prevent corals and other photosynthetic organisms—the base of the marine food web—from efficiently building their skeleta (National Research Council 2010). Here we argue that the human species has an analogous danger lurking in the shadows of global warming—a significant risk to our wellbeing and survival caused *directly* by the CO_2 forcing itself.

Occasional revision to the date of speciation notwithstanding, the full existence of the biological species *Homo Sapiens* (or so–called anatomically modern humans) is well covered by the record of atmospheric CO_2 concentration derived from air bubbles in Antarctic ice cores (Fig. 1). Prior to the Industrial Revolution and going back about 800,000 years, atmospheric CO_2 concentration bounced between about 200–300 parts per million (ppm), reaching a lowest value of 172 ppm seven ice ages ago and a peak of 300 ppm three interglacials ago (Lüthi *et al.* 2008). The nearly 50% increase in CO_2 concentration between 1813 (280 ppm) and 2018 (409 ppm) is easily attributed to human emissions, in particular fossil fuel burning (Rubino *et al.* 2013). Superimposed on the relatively smooth exponential trend in global atmospheric CO_2 over the past several decades is a pronounced annual cycle. The predominance of land in the Northern Hemisphere means that CO_2 is withdrawn from the atmosphere as a whole throughout boreal summer (while the majority of Earth's terrestrial plants are photosynthesizing) and accumulates in the atmosphere throughout boreal winter (while Northern Hemisphere plants are dormant or decomposing). The entire annual cycle of atmospheric CO_2 concentration has an amplitude of approximately 6 ppm between May and September. The increase in atmospheric CO_2 concentration over the past century due to fossil fuel emissions, by both amount and pace, is undeniably significant when compared to all of the known natural rhythms of the planet, including those that modern humans have been exposed to.

What are the *direct* effects on humans of elevated ambient CO_2 concentrations? Almost entirely decoupled from the climate research enterprise is a growing literature on the effects of CO_2 exposure on cognitive function. Practical interest in the matter is as old as the infamous "Keeling Curve" of CO_2 from Mauna Loa itself, but for rather different reasons. Early experimental studies testing for the influence of relatively high concentrations of CO_2 (5–8%) that might be present in confined and enclosed spaces like submarines found significant impacts on ability to respond to a stimulus (Harter 1967), reasoning (Sayers *et al.* 1987) and threat processing (Garner *et al.* 2011). More moderately elevated concentrations (2.5%), such as those that may be present in passenger automobiles and aircraft, have been shown to impair visual perception (Yang *et al.* 1997) and ability to maneuver an aircraft (Allen *et al.* 2018).

The last decade saw the CO_2–cognition literature turn an eye toward densely–populated indoor spaces with varying levels of ventilation, such as schools and office buildings. Studies focusing on school environments have found impacts of CO_2 on standardized test scores (Haverinen–Shaughnessy and Shaughnessy 2015) and attendance (Schendell *et al.* 2004), and significant deterioration of attention, vigilance, memory and concentration when CO_2 levels are elevated (Bakó–Biró *et al.* 2012). In simulating office–like environments under different environmental conditions, several studies have found significant reductions of cognitive performance even under commonly observed indoor CO_2 levels relative to typical ambient outdoor levels (Satish *et al.* 2012; Zhang *et al.* 2015; Allen *et al.* 2016; Hong *et al.* 2018).

One recent study was especially useful for understanding the effects of CO_2 in work and school settings as it exposed participants to controlled levels of CO_2 over a time period corresponding roughly to a day of work or school (6 hours) and used a powerful within–subjects design to assess how increasing CO_2 concentrations affected cognition in each individual (Allen *et al.* 2016). The study evaluated a range of high–level cognitive domains, including decision making, strategizing and crisis response. Three exposure conditions were applied: CO_2 concentrations of 550 ppm, 945 ppm and 1,400 ppm. For modern context, 550 ppm is only ~34% higher than the average global atmospheric (outdoor) CO_2 concentration in 2018 (409 ppm), 945 ppm is consistent with American Society of Heating, Refrigerating and Air–Conditioning Engineers ventilation guidelines for acceptable indoor air quality (ASHRAE 2016), and 1,400 ppm is consistent with an average concentration measured in U.S. public and commercial office buildings in the mid–1990s according to the U.S. Environmental Protection Agency (EPA) but is much lower than concentrations that have been measured in poorly–ventilated school buildings (Bakó–Biró *et al.* 2012). Systematic relationships were found between most of the cognitive function scores and CO_2 concentration, including from 550–945 ppm and from 945–1,400 ppm. Across the full domain of CO_2 concentrations, the apparent statistical relationships varied from linear declines in cognitive function scores with CO_2 concentration (*e.g.*, overall ability to make decisions) to nonlinear, wherein the decline in cognitive score is more pronounced between 945 ppm and 1,400 ppm (*e.g.*, complex strategizing). Not only were such reductions in cognitive function score statistically significant, they were typically rather large—on the order of tens of percent decrease in performance per ~400 ppm CO_2 increase (equivalent to a doubling of present–day outdoor CO_2 concentration). Many areas of cognition have not been found to be so severely affected—or in some cases affected at all—by increased CO_2 (Stankovic *et al.* 2016), but these processes in the domain of decision making and planning appear to be robustly affected (Allen *et al.* 2016; Satish *et al.* 2012; c.f. Rodeheffer *et al.* 2018). More work will be needed to determine which cognitive processes are susceptible to the effects of increased CO_2 and under what conditions.

Studies like Satish *et al.* (2012) and Allen *et al.* (2016) are representative of a growing body of scientific evidence pointing to CO_2 as a pollutant—not just a proxy for ventilation rate—with direct detrimental impacts on the cognitive function of humans in schools and offices. How might CO_2 lead to these cognitive deficits? High levels of CO_2 in the air result in reduced gas transfer and increased CO_2 in the alveoli of the lungs, which diffuses into the blood, crossing the blood–brain barrier (Shriram *et al.* 2018; Azuma *et al.* 2018). Increased CO_2 in the blood (hypercapnia) within the brain is associated with reduced oxygen (hypoxemia) and brain activity indicating decreased arousal and excitability (Woodbury *et al.* 1957; Xu *et al.* 2010). CO_2 is known to increase sleepiness (Vehviläinen *et al.* 2016) and anxiety (Bailey *et al.* 2005), both of which in turn harm cognitive function (Zhang *et al.* 2015; Dinges and Kribbs 1991; Vytal *et al.* 2012). Robertson (2001) argued that even modestly elevated concentrations of atmospheric CO_2 (720 ppm) are sufficient to induce acidosis (lowered blood pH) in humans, leading to symptoms like restlessness and mild hypertension—eventually somnolence and confusion. A study in juvenile rodents found that increased CO_2 in the air reduced levels of a neuroprotective growth factor, severely harming brain development, increasing anxiety and impairing learning and memory (Kiray *et al.* 2014). Though these studies provide some insight into the effects of CO_2 on the brain, much work is still needed to understand the full mechanistic chain from increased CO_2 in the air to specific impaired cognitive processes.

A possible explanation for the apparent decoupling of the scientific literature concerning CO_2 impacts on human cognitive function and that of anthropogenic climate change is that the vast majority of the former research focuses on *indoor* air quality and health (see review by Azuma *et al.* 2018). Note that CO_2 concentrations in buildings are a result of the combination of CO_2 infiltrating from outdoors inside, or brought in with the ventilation system outside air, and the CO_2 generated by the building occupants. Typical indoor concentrations are similar to outdoor levels if the occupancy is sparse and could be much higher if the building has high occupancy and poor outdoor air supply. How does the scale of the modern–day rise in global atmospheric CO_2 concentration compare to the experimental conditions in the aforementioned cognitive studies? It is unclear whether the rise from ~280 ppm to 409 ppm since 1813 due to anthropogenic emissions would have caused a detectable decline in human cognitive function, since most studies used today's ambient outdoor air as the control case (*i.e.*, 'ventilated' or 'low–CO_2' condition). But society's uncertain energy future provides a compelling set of grand experiments—one of which will definitely be conducted.

A set of four representative concentration pathways (RCPs) were conceived under the auspices of the Intergovernmental Panel on Climate Change (IPCC), primarily to be used as prescribed inputs to comprehensive, fully–coupled climate and Earth system models (*i.e.*, simulating the global atmosphere, ocean, and so on) to answer questions about how much will the world will warm, what the impacts will be, and how their severity depends on future CO_2 emissions. In IPCC parlance, the acronym RCP is followed by a number that refers to the amount of additional energy (or 'radiative forcing') in the Earth system by the year 2100 (*e.g.*, 4.5 W/m^2 with RCP4.5), but these are also associated with future trajectories of global carbon dioxide (and other greenhouse gas) emissions and resultant concentrations. The endpoint CO_2 concentrations in 2100 for RCP2.6, RCP4.5, RCP6 and RCP8.5 are 420 ppm, 540 ppm, 625 ppm and 930 ppm, respectively (van Vuuren *et al.* 2011). While it may be too early to tell which RCP will become closest to reality, RCP8.5 is widely considered to be the business–as–usual scenario, and global emission estimates to date do not point to a detectible divergence from that pathway (Le Quéré *et al.* 2018). Interestingly, the middle CO_2 condition used in the Allen *et al.* (2016) study of indoor CO_2 effects on cognitive function, which was aimed at industry guidelines for indoor air quality, is almost exactly the predicted *outdoor* concentration in 2100 under RCP8.5. Did Allen *et al.* (2016) accidentally generate a prediction of the impact of business–as–usual CO_2 emissions on *outdoor* human cognitive function at the end of this century?

Predicting future societal behavior and quantifying the impact of air chemistry on the brain are obviously complex and uncertain endeavors. The third and equally complex link is that between outdoor and indoor air, which is a concern of building and air quality engineers. This relationship can be modeled semi–empirically using a "box–model" differential equation of the form

$$(1) \qquad V\,\mathrm{d}C/\mathrm{dt} = Q\,(\,C_{out} - C\,) + G,$$

where V is the volume of the indoor space, C is the concentration of CO_2 in the indoor space, Q is the outdoor air ventilation rate (volume per time), C_{out} is the outdoor CO_2 concentration and G is the rate of generation of CO_2 occurring in the indoor space—respiration by human occupants of the indoor space (Persily and de Jonge 2017; Persily 2018; Miller 2018). This model assumes that the indoor space is well mixed, a reasonable assumption under many circumstances. The steady–state solution to (1) is obtained by setting the time derivative to zero, and rearranging for C yields

$$(2) \qquad C = G/Q + C_{out}.$$

Therefore, in steady state, indoor CO_2 concentration is independent of room volume and number of occupants, always at least as high as the outdoor concentration (as neither generation nor ventilation rate can be negative) and simply scales with the ratio of generation to ventilation. For reasonable values of G and Q for elementary school students (0.004 L/s per student) and classrooms (10 L/s per student), respectively, a ratio G/Q equates to 400 ppm (Persily and de Jonge 2017; Persily 2018). Under such assumptions, then, an outdoor CO_2 concentration of 409 ppm (as in 2018) would equate to 809 ppm inside the classroom upon reaching equilibrium.

With predictions of future outdoor CO_2 concentrations informed by IPCC–related efforts, an idealized yet physically–based model of the indoor–outdoor concentration relationship, and estimates of various CO_2–cognition relationships derived from recent quantitative experiments on humans, we can roughly estimate the impact of future fossil fuel emissions on human cognitive function, including how it unfolds throughout the century and how it depends on mitigation strategies (Fig. 2). Here we offer a straightforward demonstration, applied to elementary school classrooms, achieved by solving (2), assigning reasonable parameters of generation rate G and ventilation rate Q, prescribing transient predictions of outdoor CO_2 concentration C_{out} associated with RCPs, and fitting simple functions to robust human subject research results (Allen *et al.* 2016). The end–to–end model is thus one predicting *indoor* cognitive performance (for the particular studied cognitive processes) as a function of *outdoor* CO_2 concentration. Under these assumptions, the model predictions are quite arresting. On the business–as–usual CO_2 emission pathway (RCP8.5), we may be in for a ~25% reduction in our basic decision–making ability, and a ~50% reduction in more complex strategic thinking, by the year 2100. These results are almost entirely avoidable by reducing global CO_2 emissions according to RCP4.5, which would require adopting goals set forth under the Paris Agreement of the United Nations Framework Convention on Climate Change (UNFCCC).

Of note is that the U.S. building sector is a large contributor to CO_2 emissions. In 2015, CO_2 emissions from fossil–fuel combustion in buildings generated 8.6% of total U.S. greenhouse gas emissions; buildings were the fourth highest emitting sector after electric power, transportation, and Industry (C2ES 2017). Factoring in the indirect emissions from the use of electricity generated off–site residential and commercial buildings account for 29% of total U.S. emissions (U.S. Environmental Protection Agency 2017). Within the building sector itself, space heating, ventilating and cooling accounts for 30–38% of the CO_2 emissions (U.S. Energy Information Administration 2018). An inventory of greenhouse gas emissions from 2015 found that New York City buildings accounted for 67% of the city's emissions (The City of New York 2017). It is ironic that much of the CO_2 emissions come from the use of energy in buildings and yet the developed world spends 90% of our time in these essential buildings that protect us from the elements, where we are constantly exposed to air pollutant emissions from cooking, household products, building materials, occupant activities, outdoor air pollution brought indoors by ventilation, and the CO_2 that we generate indoors as part of our metabolic processes.

Fossil fuel emissions will continue to have unforeseen consequences for Earth and its inhabitants. As we move closer and closer to experiencing the full scale of climate change, we must consider all impacts including those where CO_2 exerts its effects directly and without regard to Earth's so–called climate sensitivity, as with human cognition. Although the above model is relatively straightforward and makes some simplifying assumptions, and the calculations should be considered back–of–the–envelope, they illuminate the principle dynamics and uncertainties involved in understanding and predicting the impact of fossil fuel combustion on human cognition. Broad, interdisciplinary teams representing economics and energy policy continue to refine our projections of CO_2 emissions through integrated assessment models. Building and air quality engineering is key to understand the exchange of air between the outdoors and the built environment; moreover, physiology determines the rate of CO_2 generation by its occupants. Finally, there is a clear need for additional experimental studies quantifying the human cognitive response across a broad spectrum of cognitive domains, especially to CO_2 concentrations between 500 and 2,000 ppm. Just like ocean acidification, reduced cognitive function is one of the 'hidden' climate change impacts where warming needn't play middleman, and it will manifest in classrooms, offices, hospitals, the transportation sector, and many other populated indoor spaces. Though improved ventilation could be an adaptation measure to mitigate these consequences in some situations, ventilation is not helpful when outdoor air is highly polluted (due to climate change or other factors), and ventilation already comes at the cost of a substantial fraction of building energy consumption. The best way to prevent indoor CO_2 levels from reaching harmful levels is through reduced fossil fuel emissions.

Data Availability Statement

All data are publicly available and/or drawn from primary sources cited in the main text.

Historical measurements of atmospheric carbon dioxide concentration (used in Figure 1) are available at http://ncdc.noaa.gov/paleo/study/17975 and https://www.esrl.noaa.gov/gmd/ccgg/trends/data.html. Future estimates of atmospheric carbon dioxide concentrations associated with RCP4.5 and RCP8.5 (also used in Figure 1) are available at http://www.iiasa.ac.at/web-apps/tnt/RcpDb/.

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Figures

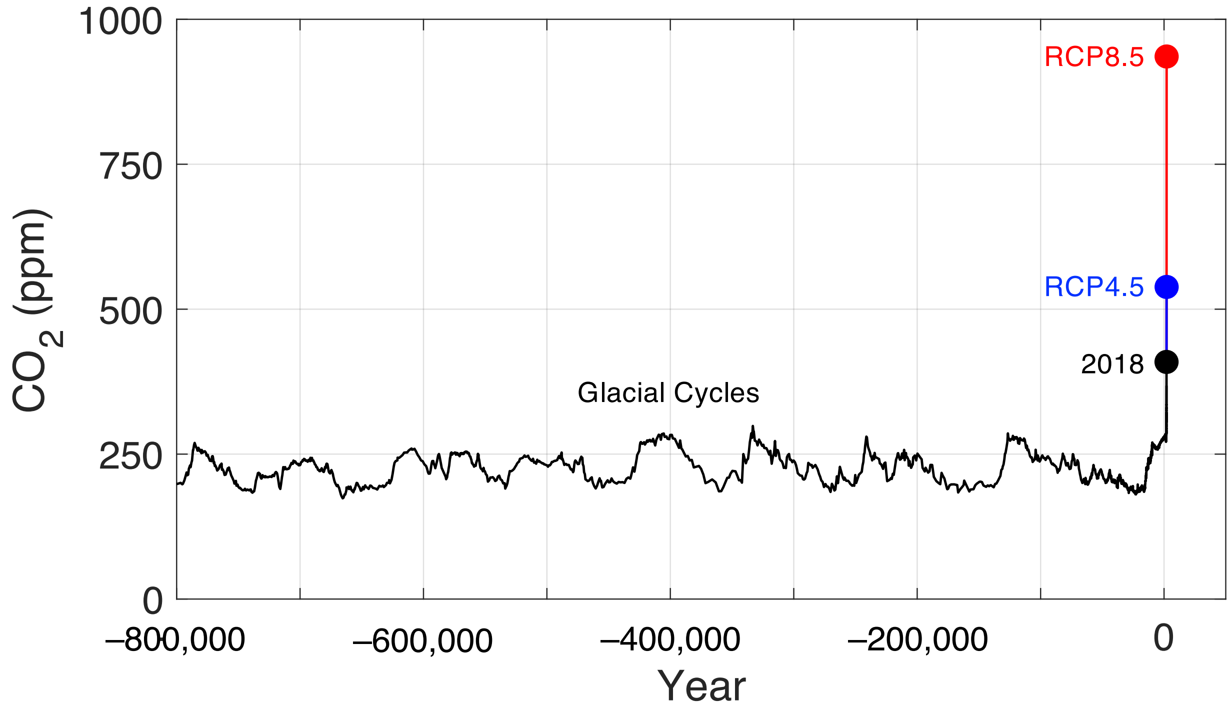

Figure 1. Carbon dioxide past, present and future. Atmospheric concentration (ppm) of CO$_2$ derived from Antarctic ice cores (Lüthi *et al.* 2008), measured directly at Mauna Loa Observatory, and future concentrations associated with Representative Concentration Pathway (RCP) 4.5 and 8.5 (van Vuuren *et al.* 2011).

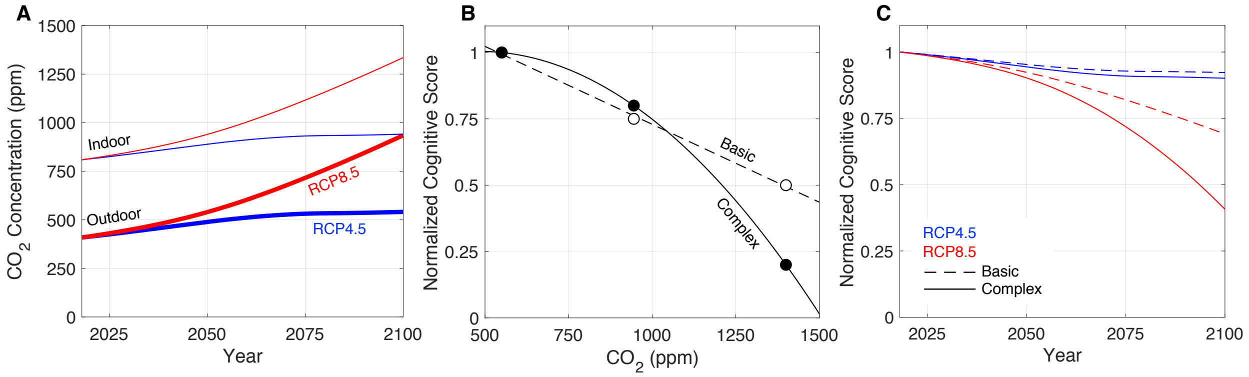

Figure 2. Modeling the effect of anthropogenic CO$_2$ emissions on cognitive function. Future outdoor CO$_2$ concentrations (ppm) associated with RCP4.5 and RCP8.5 (thick lines) along with equivalent, steady–state indoor CO$_2$ concentrations (thin lines) assuming reasonable values of generation and ventilation rates (**A**). Empirical models of cognitive function scores (normalized) for basic engagement and ability to make decisions in a task (dashed line) and complex strategy (solid line) as a function of indoor CO$_2$ concentration, derived from the *Basic Activity Level* and *Strategy* measures in Allen *et al.* (2016) (**B**). Projected cognitive function scores (normalized) for basic cognitive measure (dashed lines) and complex strategy (solid lines) assuming RCP4.5 (blue lines) and RCP8.5 (red lines) (**C**).