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RESEARCH ARTICLE
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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

Correspondence to:
K. B. Karnauskas,
kristopher.karnauskas@colorado.edu

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Fossil Fuel Combustion Is Driving Indoor CO_2 Toward Levels Harmful to Human Cognition

Kristopher B. Karnauskas[1,2,3], Shelly L. Miller[4], and Anna C. Schapiro[5]

[1]Cooperative Institute for Research in Environmental Sciences, University of Colorado Boulder, Boulder, CO, USA, [2]Department of Atmospheric & Oceanic Sciences, University of Colorado Boulder, Boulder, CO, USA, [3]Department of Environmental & Occupational Health, Colorado School of Public Health, Aurora, CO, USA, [4]Department of Mechanical Engineering, University of Colorado Boulder, Boulder, CO, USA, [5]Department of Psychology, University of Pennsylvania, Philadelphia, PA, USA

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.

The vast majority of the impacts of anthropogenic climate change on human health and society are *indirect* to the carbon emissions, for example, increased mortality due to more frequent heat waves is an expected outcome, but humans are not adding significant heat directly to the atmosphere. Modern human activity emits greenhouse gases, which raise the near-surface air temperature via the greenhouse effect and make heat waves more probable (Gasparrini et al., 2017; Stott et al., 2004). Consider the loss of habitat due to sea level rise. The absorption and omnidirectional reradiation of longwave radiation associated with increasing concentrations of greenhouse gases such as carbon dioxide (CO_2) in the atmosphere cause 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 emissions, with atmospheric warming playing a prominent role along the chain of causality.

But not *all* impacts are brokered by warming. 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 well-being and survival caused *directly* by the CO_2 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 (Figure 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 2019 (411 ppm) is easily attributed to human emissions, in particular fossil fuel burning (Rubino et al., 2013) with smaller yet significant contributions from land use change and cement

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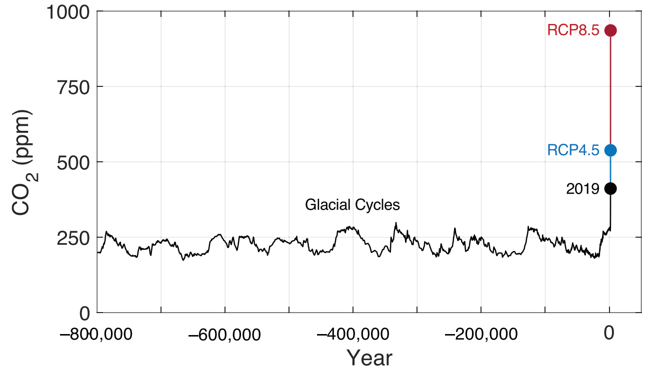

Figure 1. Carbon dioxide past, present, and future. Atmospheric concentration (ppm) of CO_2 derived from Antarctic ice cores (Lüthi et al., 2008), measured directly at Mauna Loa Observatory, and future concentrations associated with Representative Concentration Pathway (RCP) 4.5 and 8.5 (van Vuuren et al., 2011).

manufacture. 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 the 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 & Shaughnessy, 2015; Wargocki et al., 2020) and attendance (Shendell 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 (Allen et al., 2016; Hong et al., 2018; Satish et al., 2012; Zhang et al., 2015).

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 hr) 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 and planning. Three exposure conditions were applied: CO_2 concentrations of 550, 945, and 1,400 ppm. For modern context, 550 ppm is only ~34% higher than the average global atmospheric (outdoor) CO_2 concentration in 2019 (411 ppm), 945 ppm is consistent with American Society of Heating, Refrigerating and Air-Conditioning Engineers (2016) ventilation guidelines for acceptable indoor air quality, 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 but is much lower than concentrations that have been measured in poorly ventilated school buildings (Bakó-Biró et al., 2012; Wargocki et al., 2020). 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 were linear for some declines in cognitive function scores with increasing CO_2 concentration (e.g., overall ability to make decisions), and nonlinear for others, wherein the decline in cognitive score is more pronounced between 945 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 not affected at all, by increased CO_2

(Jacobson et al., 2019; Stankovic et al., 2016). It may be that higher-level, more cognitively demanding tasks are more likely to be sensitive to the effects of moderate levels of ambient CO_2. However, null or nonmonotonic effects have been found even in these demanding tasks for two special populations—submariners (Rodeheffer et al., 2018) and astronaut-like subjects (Scully et al., 2019). These results suggest that factors like increased experience with demanding cognitive tasks or physiological adaptation to increased ambient CO_2 could potentially mitigate the harmful effects of CO_2 on cognition. Much 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 part 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 (Azuma et al., 2018; Shriram et al., 2019). Increased CO_2 in the blood (hypercapnia) within the brain is associated with reduced oxygen (hypoxemia), which is critical for brain function, and brain activity indicating decreased arousal and excitability (Woodbury et al., 1958; Xu et al., 2011). CO_2 is known to increase sleepiness (Snow et al., 2019; Vehviläinen et al., 2016) and anxiety (Bailey et al., 2005), both of which in turn harm cognitive function (Dinges & Kribbs, 1991; Vytal et al., 2012; Zhang et al., 2015). 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). 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, confusion, and sleepiness. Based on the current literature, the proximal causes of impaired high-level cognition at the relevant concentrations of CO_2 thus seem likely to be increased sleepiness and perhaps increased anxiety. 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 reviews by Azuma et al., 2018 and Jacobson et al., 2019). 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. However, several studies have also measured a so-called urban CO_2 dome that forms over cities due to proximity to emission sources, primarily fossil fuel burning (Day et al., 2002; George et al., 2007; Idso et al., 2001; Jacobson, 2010; McRae & Graedel, 1979; Mitchell et al., 2018; Moore & Jacobson, 2015). For example, the 5-year study over a rural-urban transect through Baltimore, MD, by George et al. (2007) revealed a robust urban CO_2 dome with an average urban enhancement of 66 ppm; this is in the middle of the range of enhancements reported by the studies cited above. 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 to 411 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—some version 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, etc.) 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

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RCP2.6, RCP4.5, RCP6, and RCP8.5 are 420, 540, 625, 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 considered to be the unmitigated emissions 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 unmitigated 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 using a mass balance model—a differential equation of the form

$$V\,dC/dt = Q\,(C_{\text{out}} - C) + G, \quad (1)$$

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, 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 (Miller, 2018;Persily, 2018; Persily & de Jonge, 2017). 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

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

Therefore, in steady state, indoor CO_2 concentration is 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, 2018; Persily & de Jonge, 2017). Under such assumptions, then, an outdoor CO_2 concentration of 477 ppm (411 ppm as in 2019, plus a 66-ppm urban enhancement) would equate to 877 ppm inside the classroom upon reaching equilibrium. Note that in many indoor environments, the generation rate can exceed the design ventilation rate, since many spaces can become overcrowded and not ventilated appropriately, leading to even higher indoor CO_2 concentrations (Miller et al., 2009).

With predictions of future global (outdoor) CO_2 concentrations informed by IPCC-related efforts, observed estimates of urban enhancement, 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 (Figure 2). Here, we offer a straightforward demonstration, applied to elementary school classrooms in a city similar to Baltimore, MD, 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). We chose the "Basic Activity Level" and "Strategy" (*Basic* and *Complex*, respectively, in Figure 3) measures from the Allen et al. (2016) study to include in the model, as they exhibit highly consistent trends across subjects and because they provide examples of how linear (in the case of Basic Activity) and nonlinear (in the case of Strategy) effects may play out. These measures are part of the Strategic Management Simulation battery, which is a commercial product developed to test the decision-making effectiveness of employees when presented with various real-world scenarios. Lack of free access to this battery and lack of established correlations with standard cognitive measures are weaknesses of using these measures, but they nevertheless provide clear cases of impacted cognition in the context of a well-controlled experimental manipulation of CO_2 levels. The Basic measure corresponds to the number of actions taken in responding to scenarios; it is simply a measure of task engagement. The Complex measure tracks ability to strategize—to take actions in a scenario that provide the foundation for future useful actions. We believe these measures provide useful examples for proof-of-concept simulations.

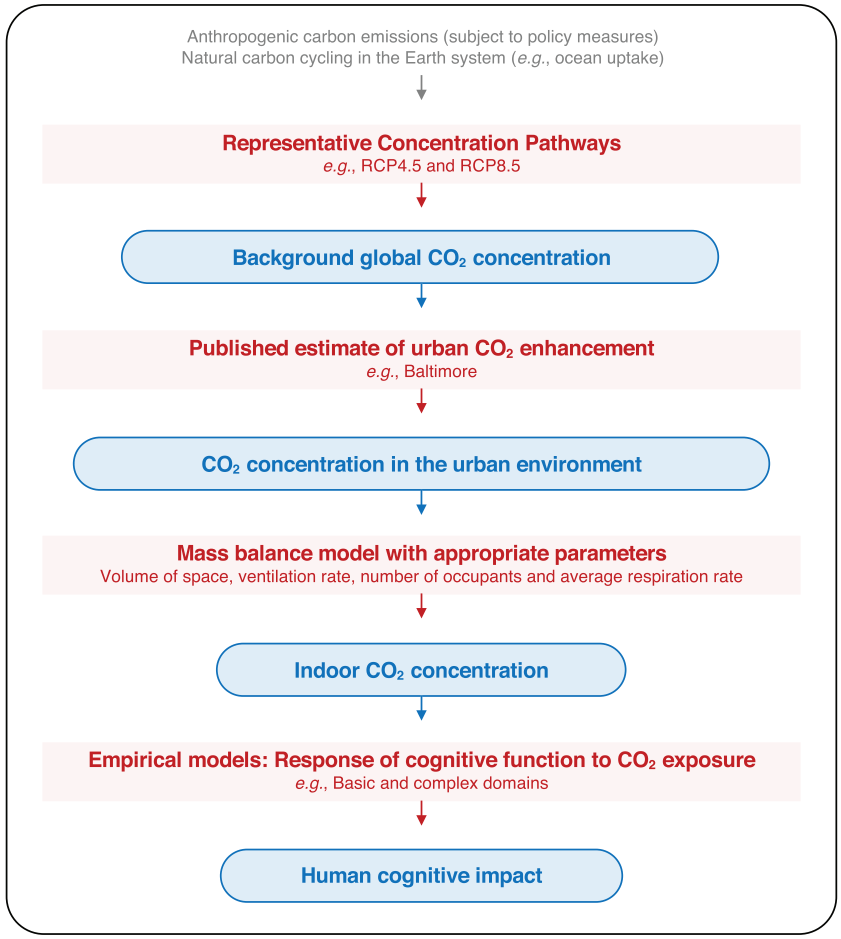

Figure 2. Flowchart describing the information and modeling required for estimating the impacts of future CO_2 emissions on human cognition. Blue elements represent quantities that result from calculations, and red elements represent intermediate steps such as observation and modeling. Smaller text within red elements gives some specifics about the simulations conducted in this study.

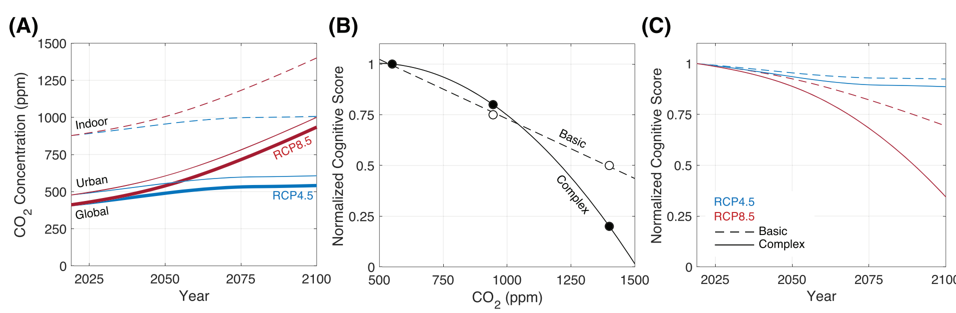

Figure 3. Modeling the effect of anthropogenic CO_2 emissions on cognitive function. Future global outdoor CO_2 concentrations (ppm) associated with RCP4.5 and RCP8.5 (thick lines), equivalent urban outdoor CO_2 concentration (thin lines), along with steady-state indoor CO_2 concentrations (dashed lines) assuming reasonable values of generation and ventilation rates (a). Empirical models of normalized cognitive function scores (where normalized refers to the normalization of observations in Allen et al., 2016, such that scores are adjusted to 1.0 at ~500 ppm and bounded [0, 1]) 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). The dots in panel (b) denote the anchor points extracted from Allen et al. (2016) used for fitting the two models (open for *Basic Activity Level* and filled for *Strategy*). Projected normalized cognitive function scores for basic cognitive measure (dashed lines) and complex strategy (solid lines) assuming RCP4.5 (blue lines) and RCP8.5 (red lines) (c). In panel (c), all curves are adjusted to begin at 1.0 in year 2019, thus facilitating a comparison of the changes over time relative to present.

The full end-to-end model thus predicts *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 (Figure 3). On the unmitigated CO_2 emission pathway (RCP8.5), we may be in for a ~25% reduction in our indoor basic decision-making ability and a ~50% reduction in more complex strategic thinking, by the year 2100 relative to today. These results are almost entirely avoidable by reducing global CO_2 emissions according to RCP4.5, which is tantamount to achieving the broad goals set forth under the Paris Agreement of the United Nations Framework Convention on Climate Change (UNFCCC).

While the above model calculations are forward-looking based on *projections* of CO_2 concentration, it is interesting to consider the impact that CO_2 emissions *to date* may have had on human cognition. Interpreting the increase in global atmospheric CO_2 since the Industrial Revolution (280–411 ppm from 1813–2019) using the models shown in Figures 3a and 3b, we estimate that our basic engagement and decision-making ability should have been reduced by about 8% (or 13%, if the urban CO_2 dome effect is both entirely anthropogenic and developed over the same time period). It is important to note that this is an estimate of the influence specifically of the rise in CO_2 concentration, all other factors being equal. In reality, IQ scores have been increasing since at least the beginning of the twentieth century due to changes in other factors such as education, technology, and nutrition (Pietschnig & Voracek, 2015).

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 (Center for Climate and Energy Solutions, 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 account 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 unfortunately cyclic 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 sources such as 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 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 (i.e., all of the red elements in the flowchart, Figure 2). Broad, interdisciplinary teams representing economics and energy policy continue to refine our projections of CO_2 emissions through integrated assessment models. Long-term regional observations and modeling are needed to further constrain the urban and suburban enhancement of global, background CO_2 concentrations. Building, air quality, and energy engineering are key to understand the exchange of air between the outdoors and the built environment and to reduce energy consumption in buildings due to heating and cooling; 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, and over longer periods of time, to assess potential for physiological adaptation. 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 especially 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 levels harmful to cognition is through reduced fossil fuel emissions.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

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 the websites (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 the website (http://www.iiasa.ac.at/web-apps/tnt/RcpDb/).

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