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Title: Possible future impacts of elevated levels of atmospheric CO_2 on human cognitive performance and on the design and operation of ventilation systems in buildings.

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Abstract

This paper brings together a rapid evidence assessment of impacts of elevated CO2 concentrations on human cognition with IPCC projections of atmospheric CO2 concentration by the end of the present century, and an analysis of potential consequences of increased atmospheric CO2 concentrations for ventilation systems in buildings and other enclosed spaces. Whilst only limited research has been done on the effect of CO2 on cognition (as opposed to air quality in general), half of the studies reviewed indicate that human cognitive performance declines with increasing CO2 concentrations. Hence, given the likelihood of increasing atmospheric CO2 concentration by the end of the 21st century, direct impacts of anthropogenic CO2 emissions on human cognitive performance may be unavoidable. Attempts to minimize these direct impacts are likely to result in significant indirect impacts on the engineering of ventilation systems and associated energy use in all enclosed spaces including buildings and transport systems.

Keywords:

Carbon dioxide, Ventilation, Indoor Air Quality, Building energy consumption

Practical Application

This paper concerns what may well be one of the most important long-term drivers of the design, management, operation and regulation of ventilation systems over the remainder of the 21st Century. It will be relevant to professionals, particularly at senior levels in the building industry.

1. Introduction

The literature on climate change describes in detail a wide range of routes from increased CO_2 concentrations to impacts on humans (1,2). These can be grouped under the following headings:

- Direct impacts of climate change on humans (effects of changes in external temperature, humidity, wind speed, rainfall etc.).
- Impacts mediated by agricultural systems (changing availability of foodstuffs, changing distribution of agricultural systems).
- Impacts mediated by changes to natural terrestrial ecological systems (e.g. changes to distribution of disease vectors – but note that agricultural systems, natural eco-systems and energy systems all interact).
- Impacts mediated by changes to sea level and ocean acidity and patterns of circulation.
- Impacts of attempts to mitigate climate change (these have so far been modest, but in principle they will affect and be mediated by changes to all categories of human infrastructure).

The likelihood that elevated atmospheric CO_2 concentrations might impact directly on humans has received little attention in the scientific literature. Two of the few exceptions are Nazaroff who states that climate change will affect the concentrations of air pollutants in buildings which might have health and well-being implications (3), and Gall and Nazaroff who suggest impact on productivity (4).

This paper systematically reviews studies that have tested the direct impact of elevated CO_2 concentrations on human cognition. The paper is in three parts. The first part establishes the range of possible CO_2 concentrations by the end of the 21st century. It is followed by a rapid evidence assessment on direct impacts of CO_2 on human cognitive performance. Importantly, only those studies that indeed allow statements on a causal effect on CO_2 on human cognition are considered; studies that use CO_2 as an indicator for air quality in general are excluded. The third part reviews the basis for the design of ventilation systems in buildings and other enclosed spaces and estimates the range of impacts of higher background CO_2 concentrations on the design, operation and energy consumption of ventilation systems.

2. Long term trends in atmospheric CO_2

Projections published by the Intergovernmental Panel on Climate Change (IPCC) and their discussion in academic literature form the basis for the range of identified possible CO_2 concentrations. The IPCC is a scientific and intergovernmental body under the umbrella of the United Nations that provides a scientific view of climate change and its political and economic impacts in regular assessment reports based on published studies. Building on earlier work by Meinshausen et al. (5), the IPCC in its 5th Assessment Report has defined four ‘representative concentration pathways’ (RCPs), based on different trajectories of atmospheric concentrations of greenhouse gas (not emissions), to map out the range of possible climate futures (6). Levels of CO_2 corresponding to each of the RCPs in 2100 are roughly 415, 540, 670 and 955 ppm CO_2 - see Figure 1 (6). We note that simple extrapolation of historical trends in CO_2 emissions suggests atmospheric CO_2 levels in excess of 1,000 ppm by 2100 (7), which is broadly consistent with RCP8.5.

All four RCPs would see increased atmospheric CO_2 concentrations compared to levels today. Given the history of global emissions, a future trajectory similar to

RCP8.5 cannot be dismissed as unlikely. While the 2015 Paris agreement expresses the aspiration to stay below 2°C warming and a recent paper showed that it would still be physically possible to reach this goal (8), other research is more sceptical (9), typically indicating only a 5% chance of reaching this target (10). The stringent mitigation scenario of RCP2.6 which is consistent with keeping global warming below 2°C above pre-industrial temperatures, would require deployment of negative emissions technologies (NETs) (6) at a large and possibly infeasible scale (11). It appears that any of the three lower pathways would require unprecedented transformations in patterns of economic and technological development observable over the last half century and in the global effectiveness of energy and climate policy.

In addition to the likelihood of increasing planetary background CO_2 concentration, there is a risk of even larger increases in cities. All of the figures for CO_2 concentrations given above refer to the mean planetary background concentration, for which measurements taken at the Mauna Loa observatory are used as an approximation. However, monthly mean CO_2 concentrations in London are up to 25 ppm higher than the Mauna Loa time series, with peaks in months dominated by atmospheric stability (12), while concentration excesses in urban areas averaged over shorter periods can be in excess of 100 ppm (13). One would expect urban CO_2 concentration excesses in CO_2 emissions to scale in rough proportion to global CO_2 emissions – thus in an RCP8.5 world, one might expect urban CO_2 concentration excesses in 2100 to be roughly three times as high as at present, leading to concentrations in cities of the size of London above 1,000 ppm for several months per year. The next part of the paper indicates the potential effect on human cognitive performance of such increases in CO_2 concentrations.

3. Impacts of CO_2 on cognitive performance

3.1. Background to CO_2 in buildings.

The toxicology of CO_2 at high concentrations such as 50,000 ppm (5%) is well understood. Much of the basic science has been undertaken by the military who among other things, have needed to establish safe operating conditions for submariners, pilots and astronauts (14). The literature indicates that the main mechanism at work at very high concentrations, is central nervous system depression (15), which ultimately leads to loss of consciousness at concentrations above 10% and death at concentrations above 17%. But, a concentration of 5% is more than 120 times the current atmospheric concentration, and more than an order of magnitude higher than the levels commonly encountered in buildings – thus of limited relevance to the subject matter of this paper.

Work place limits on CO_2 concentration are typically in the region of 5,000 ppm (16) but significantly lower levels are recommended for buildings. The earliest scientifically-backed recommendation for an upper limit on CO_2 in dwellings, of 1,000 ppm, was due to Pettenkofer (17), and was made in the context of rapid industrialisation and of associated attempts by the emerging discipline of Public Health to improve conditions in overcrowded dwellings. Pettenkofer makes clear that his choice of CO_2 as a metric for indoor air quality was because it was easily measured and directly related to density of human occupation, but he was unable to separate out the effects of CO_2 alone.

In the 20th and 21st centuries, national and international standards institutions and professional organisations responsible for setting ventilation and indoor air quality standard have continued to recommend maximum indoor CO_2 concentration in the region of 1,000-1,500 ppm. The standards themselves and the background literature show that these organisations have continued to view CO_2 at these levels primarily as a useful proxy for other more problematic, but more-difficult-to-measure pollutants such as human body odour, rather than as a pollutant in its own right (13,18–20).

On the basis of the evidence available to these organisations, and in particular in view of the lack of evidence for direct impacts of CO_2 at levels two orders of magnitude below the lethal concentration, this can be judged to have been a rational approach. Though not explicit in standards documentation, a logical consequence of taking CO_2 as a proxy for ventilation rather than a pollutant in its own right, is that ventilation systems in buildings should be designed around the concept of CO_2 concentration excess, $[CO_{2,in}] - [CO_{2,background}]$, rather than absolute $[CO_{2,in}]$. If the logic were followed rigorously, this would in turn lead to a progressive increase in maximum indoor CO_2 concentrations as the external background CO_2 concentration rose over the coming century. That this has not been proposed by the primary regulatory bodies of the US, the UK and Germany, probably reflects the relatively slow rate of increase of atmospheric CO_2 over the 20th century.

3.2. Rapid evidence assessment on the effects of CO_2 on performance

A large body of research using CO_2 as a proxy for air quality has shown effects of air quality on performance. Generally speaking, higher CO_2 is associated with decreased performance (21–25). However, in these studies, variations in CO_2 are confounded with variations in other pollutants, so that no specific causal effect can be ascribed to CO_2.

The authors conducted a rapid evidence assessment (REA) of studies in which CO_2 alone was varied. REA is a systematic way of searching and integrating research on a narrowly defined topic by using systematic review methods. REAs aim to be rigorous in how they go about finding and reviewing literature, with the aim of reducing selection and publication bias; for example, search terms and databases to be searched are explicitly defined prior to the search, and specific criteria set out for which studies to include (26). The authors developed a review protocol before conducting the review, and included studies written in the English language that document empirical, quantitative findings on the effect of CO_2 on objective performance in humans. The following were excluded:

- Studies that documented qualitative findings only.
- Studies that did not report empirical results (e.g. include only modelled effects).
- Studies that focused exclusively on specific sectors and populations, e.g. aerospace and diving.
- Studies that exclusively tested animals.

3.2.1. Search methods for identification of studies

One recent publication on the effect of CO_2 on performance was used to generate keywords for the search protocol (27). The identified terms (see Table 1) were searched for in title, abstract, and keywords.

The following bibliographic databases were searched:

- Scopus
- Web of Science (all databases)

3.2.2. *Selection of suitable studies*

Results from the two databases were imported into systematic review software EPPI-Reviewer, and screened by the second author according to the above inclusion and exclusion criteria, initially title and abstract, and then full paper, see Figure 2. During full-text screening, one reference was added as it came up repeatedly in the reviewed studies as a reference and upon reading its abstract it was clear it met the screening criteria. Thus, at this stage, a total of ten studies were identified for extraction of key characteristics.

From the ten studies, the following information was extracted:

- Geographical location of study
- What type of setting the study took place in
- Study period (year)
- Study design (experimental design, case study, etc.), including the levels of CO_2 at which testing took place
- Characteristics of sample
    - Number and type of participants
    - Sampling method
    - If paid for participation
- Dependent variables (outcomes)
- Results, interpretations and main conclusions.

Inspection and comparison of the extracted data revealed that not all of the ten publications that had been retained after full-text screening (27–36) contained unique data sets: the same data had typically been published more than once, first as a conference paper and then in greater detail as a journal article[i]. In this review, only one publication per data set was considered, the latest and most detailed one. This reduced the literature to five publications, all of them journal articles (27,28,32,35,36).

3.2.3. Results of the identified studies

All investigations described in these papers had taken place in laboratory settings using experimental designs, with CO_2 concentration manipulated through addition of pure CO_2. All used a within-subject design; participants opted-in for the study, and were blinded to the CO_2 concentration level to which they were exposed. Only cognitive performance outcomes are reported (i.e. no physiological effects).

Table 2 summarises key aspects of the selected five studies. If not specified otherwise, testing of different conditions occurred on the same day. The term ‘ ‘counterbalanced’ refers to an experimental design in which the various CO_2 concentrations are tested in all possible orders.

Three of six experiments reported in the five publications found a significant effect of CO_2 on cognitive performance. A quantitative integration, i.e. meta-analysis, is difficult mainly for two reasons: 1) the papers tested performance at inconsistent levels of CO_2, so to allow comparison across studies would require the assumption of a clearly linear relationship between increase of CO_2 and change in performance; 2) the outcome measures used varied significantly.

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[i] One paper was excluded as it focused on physiological effects of CO_2 (34), and whilst it mentioned cognitive effects, too, these were reported in more detail in another paper (32) which was included in the review.

In the following, results for each study are presented in more detail. Two studies, Zhang et al. (32,35), did not find any effects whatsoever of CO_2 level on performance despite using CO_2 levels that exceeded those in other studies finding an effect (27,28) and employing a range of well-established and varied tasks. Whilst testing took place over 255 and 153 minutes, respectively, i.e. for some tests after relatively short exposure to the respective CO_2 level, this is unlikely to explain the absence of an effect, given that for other tasks testing occurred over prolonged periods. The sample size of one of their studies (32) was the largest of all reviewed studies; and the authors reported that due to repeated measures, the power was even higher in the study with 10 participants (35).

In Kajtár et al. (36), participants had to proofread a text, with numbers of rows read and errors found as outcome measures, reflecting a quantity and quality aspects, similar to one of the tasks used by Zhang. Kajtár et al. did not find an effect of CO_2 on performance in the first series of experiments, but did in the second series where the difficulty of the test had been increased. The quantity aspect was not affected by CO_2 level within the first two testing periods, but was affected in the third period during which performance at only two concentrations, 600 ppm and 3000 ppm, were compared. Regarding the quality aspect, during the second 70-minute working period, the percentage of mistakes found was significantly higher in the session with 600 ppm CO_2 than at 4000 ppm, and almost statistically significant when comparing 600 ppm and 3000 ppm in the third testing session. The respective decreases were from 79% of errors found to 74%, and from 77% to 74%[ii], i.e. a 6% and 4% decrease, respectively.

[ii] The data were not reported numerically in (28), but read from a graph, hence, likely not accurate to the decimal place.

In summary, there is a small effect of CO_2 pm on proofreading in some conditions but not all. Tests at the different CO_2 concentration levels were not counterbalanced; it is conceivable that during tests at 1500 ppm, which took place first, participants were more motivated and hence compensated for any detrimental effect of CO_2 through greater effort. However, one could also speculate that a negative effect might be expected during the first session due to participants' having had less practice.

The final two studies, Allen et al. (28) and Satish et al. (27), both used the same outcome measure, the Strategic Management Simulation (SMS) tool which tests management-level employees' ability to undertake higher-order decision making (37) - arguably a more challenging task than proof-reading. Participants were given a range of scenarios (such as being mayor of a town during an emergency situation), and asked to respond to them. Based on their actions and decisions, SMS software computed scores for nine cognitive factors.

Allen et al. reported that averaged across factors, cognitive function scores were 15% lower for the moderate CO_2 day (≈945 ppm) and 50% lower on the day with CO_2 concentrations of ≈1,400 ppm than the average on those two days with ≈545 ppm. Based on the raw values provided by Satish et al., the authors of this paper calculated that average performance across all functions decreased by 13% from 600 to 1000 ppm, and by 53% from 600 ppm to 2500 ppm. The overall decline was similar in both studies, though the highest CO_2 condition was about 1100 ppm higher in Satish et al. than Allen et al. But the exposure duration was significantly longer in Allen et al. than Satish et al. Table 3 shows the rank order relationship between cognitive performance and CO_2 concentration (low, middle and high), for the different categories of cognitive performance included in the SMS tool.

In both studies, the same two cognitive functions, Information Seeking, and Focused Activity, showed no monotonic decrease in performance with increases in CO_2.

3.2.4. Summary of the Rapid Evidence Assessment

In three of the six experiments presented in the five publications, cognitive performance is impaired with increasing CO_2, with effects already present at CO_2 levels of 945 ppm. Whilst one might speculate that low task complexity might explain why Kajtár et al.(36) found only a few effects, there is no definitive explanation as to why, in contrast to Satish et al. (27) and Allen et al. (28), Zhang et al. (32,35) found no effect despite a large sample size, an extremely well designed and controlled experiment, and a range of well established tasks - though as Zhang et al. themselves suggest, the SMS as utilized by Satish et al. and Allen et al. may have been more cognitively challenging (32). Confirmation of this speculation would require explicitly comparison of scores across the various tasks, in a within-subject design, holding all other variables constant. None of the studies reported such a comparison.

This rapid evidence review indicates the need for more research in this field given the potential impact of higher CO_2 levels. Future research should examine the effect of exposure duration systematically, should test the hypothesis suggested tentatively by Satish et al. that the sign and functional form of the relationship may depend on the nature of the cognitive task by testing across a wider range of cognitive functions of varying difficulty, and should test effects in less-skilled participants. Finally, the physiological mechanisms through which CO_2 might impact on performance, and the potential for long term physiological adaptation also need to be understood – although researching the latter is likely to pose significant practical, methodological and ethical problems.

Nevertheless, the limited literature currently available on this subject, indicates that cognitive performance may decrease for complex tasks with increasing CO_2 concentrations at levels regularly measured in buildings. In the light of this, and the global scale of the potential effect, the next section of this paper briefly explores possible engineering responses and consequent impacts on energy use.

4. Implications for ventilation systems and practices in buildings

CO_2 levels are normally higher inside than outside buildings because of additional CO_2 emitted by humans, and the absence of CO_2 sinks. The level is determined in any given situation by the ventilation rate, external concentration, and magnitude and density of internal CO_2 sources (which in most buildings will consist mainly of human respiration). Ventilation rates for buildings are normally designed to prevent internally generated pollution levels reaching unhealthy or uncomfortable levels.

Ventilation systems in most buildings operate by diluting contaminated internal air with less contaminated external air. In the limit, such systems achieve perfect mixing of internal with external air, and a uniform concentration of pollutants throughout the volume of the building. The second approach to ventilation is displacement ventilation in which pollutants are removed by smooth, unidirectional (normally vertical) flow of air, with external air displacing, but not mixing with more contaminated air within the building. In practice, most practical systems have some characteristics of both approaches. For ventilation by dilution, the relationship between external air supply and CO_2 concentration is:

$$[CO_{2,design}] - [CO_{2,background}] = \dot{CO}_2/Q \qquad 1.$$

where:

$\left[CO_{2,design}\right]$ is the design maximum internal volumetric CO_2 concentration, which currently, is typically set at 1000 ppm

$[CO_{2,\ background}]$ is the atmospheric volumetric CO_2 concentration

$\dot{CO}_2$ is the rate of production of CO_2 within the enclosed volume (m^3/s), measured at internal temperature and pressure

Q is the rate of flow of external air through the space (m^3/s), measured at internal temperature and pressure, required to ensure that internal CO_2 concentration, $\left[CO_{2,in}\right]$, does not rise above $\left[CO_{2,design}\right]$

The implications of this relationship are that if $\left[CO_{2,in}\right]$ and $\dot{CO}_2$ are to remain constant as $\left[CO_{2,background}\right]$ rises, Q has to rise towards a vertical asymptote at $\left[CO_{2,background}\right] = \left[CO_{2,design}\right]$ see Figure 3. Current guidelines on indoor CO_2 concentration would therefore become unachievable at any ventilation rate when external concentrations reach 1000 ppm. For emissions pathways that approximate to RCP8.5 this will occur around the end of the 21st century.

Such a situation is unlikely to arise in practice. Pragmatically, if there were no perceived cost from higher internal CO_2 concentrations, the design maximum concentration would, as suggested earlier, be progressively increased as the background concentration increased. Conversely, if it were perceived that there was a modest cost to increased CO_2 concentrations, a compromise would probably be reached in which the increase in internal CO_2 concentration would be partially offset by increased ventilation rates Q.

For completeness, it should be noted that it is technically possible to achieve any desired CO_2 concentration in enclosed spaces using chemical scrubbers. Such a strategy would decouple air supply requirements from changes in atmospheric background CO_2 concentration. This option, which is routine in spacecraft and submarines, is currently not used in building services engineering, and would impose significant additional costs and energy use. The authors have not attempted to estimate the impact of CO_2 removal on energy use, and conjecture that this option would be applied only in buildings of high prestige. Among its probable consequences would be an additional dimension to the disparity in physical living and working conditions across the global population.

The compromise response strategy, of partial offsetting, would increase either the dimensions and capital cost of ventilation installations, or the operational and energy costs, or both, in order to handle the larger air flows required to partially offset the effect of the increased background CO_2 concentration. It is possible, with some simple assumptions, to illustrate the additional energy costs that might be incurred in the latter case. If we assume that half of the increase in $[CO_{2,background}]$ were to be offset by larger air flows (the partial offset strategy shown in Figure 3), it is straightforward to show that with $[CO_{2,design}]$ at 1,000 ppm, ventilation rates in all buildings would need to double to accommodate an increase in $[CO_{2,background}]$ from the current 400 to 1,000 ppm. Such an increase in air flow would:

- Increase energy demand for transporting air in mechanical ventilation systems, or
- Increase the area of openings required in naturally ventilated buildings, and

- Increase the energy needed for heating or cooling additional external air supply in all buildings that needed to be heated or cooled.

For buildings that require heating or cooling, the additional thermal energy that would need to be supplied or extracted would scale in proportion to the external air flow. Energy use in buildings typically accounts for ≈30% of direct energy use in industrialised countries (38). Of this 30%, the requirements of space heating and cooling account for around 20%, of which ventilation accounts for between a quarter and a half. There is a consensus among organisations involved in the development of energy strategy and policy that the built environment represents a major opportunity to reduce energy use and CO_2 emissions (39). A doubling of ventilation requirements in a constant climate could lead conservatively to a ≈25% increase in global space heating requirements and associated CO_2 emissions, at a time when national and international strategies all envisage significant overall reductions.

Estimation of the energy needed to transport air in mechanically ventilated buildings is slightly more complex. The following analysis is based on a simplified equation for the fan power P (W) needed to transport air of density ρ kg/m^3 at a rate Q m^3/s, through a 1 metre length of ductwork of diameter D m:

$$P = 0.02 \, . \frac{8\rho Q^3}{\pi^2 . D^5} \qquad 2.$$

This equation is a extension of an equation for pressure gradient given by Daly which in turn is derived from the more general D'Arcy-Weisbach equation for friction in ducts and pipes (40,41).

Thus, in mechanical ventilation systems that were designed for the current value of $[CO_{2,background}]$, a doubling of air flow rate would require an increase in fan power of roughly a factor of 8. Such an increase could be avoided by resizing of fans and ductwork. From equation 2, a doubling of air flow rate could be accommodated without an increase in fan power by a factor of $\approx 2^{3/5} \approx 1.5$ increase in fan and duct diameters.

Two observations can be made at this point. The first is that in many buildings it would be impractical to retrofit such increased ductwork. The second is that in many existing commercial buildings, the limiting factor in the sizing of ductwork is not the control of internally generated CO_2, but the transport of heat, either to provide heating or cooling. The additional air flow needed to transport heat is typically supplied by recirculating internal air through the mechanical ventilation system. The flow rate of recirculated air is typically greater than the flow rate of fresh external air, particularly where heating and cooling loads are high. In such buildings, it may well be that additional external air could be transported in existing ductwork with no increase in fan power. Buildings in which this would not be the case would be likely to be domestic or of domestic scale, or to have been designed in such a way that requirements for heating and cooling were low – in other words, to be comparatively energy efficient.

Many buildings in temperate climates are naturally ventilated. A doubling of ventilation rates in such a building could be accommodated by doubling the cross sectional area of ventilation openings in the building’s thermal envelope. This could either be achieved by resizing or increasing the number of purpose-made openings (such as trickle vents), or in cases where air flow is controlled by window opening, simply by opening windows wider. In many existing naturally ventilated buildings, it would be straightforward to retrofit larger purpose-made openings. The authors suspect that retrofitting of some existing naturally ventilated buildings, as an alternative to fitting mechanical cooling, is more likely to be undertaken as a response to higher external temperatures associated with climate change, than by demands for greater ventilation.

It should be clear that to take this quantitative analysis significantly further would involve the consideration of a series of imponderables. But what can be concluded qualitatively is that in some mechanically ventilated buildings in some climates, the increase in fan power could approach an order of magnitude, while in others it might be small or zero. Similarly, some naturally ventilated buildings will need to be retrofitted to increase the cross-sectional area of openings (either purpose-made, or through the greater opening of windows), while in other naturally ventilated buildings such action might be overtaken by requirements of, and opportunities provided by the retrofitting of mechanical cooling.

It is clear from the above that as external CO_2 levels rise, any attempts to contain the consequent rise of internal CO_2 concentrations will require significant additional energy use, for heating and cooling additional volumes of air, and for air transport. To the extent that heat and electricity are not produced from low or zero CO_2 sources, this will result in an additional positive feedback mechanism driving climate change.

5. Discussion and conclusions

As noted earlier, the core literature on impacts of elevated concentrations of CO_2, including successive IPCC assessment reports, have framed the problem primarily in terms of direct impacts on climate, of mainly indirect impacts on natural and engineered ecological systems, and of consequent indirect impacts on humans. There is however, little in the literature that refers to direct impacts of increased CO_2

concentrations on humans or on infrastructure. The authors believe that the present paper is the first to identify and quantify the potential for such impacts in buildings, and to review evidence that they may be detectable within the timeframe of the present century.

There are clearly many uncertainties in the analysis presented here and the underpinning literature. The assertion that increased CO_2 concentrations can degrade cognitive performance is key – the literature on the subject amounts to only a few publications (27,28,32,36) and includes both positive and null effects.

Despite the limited evidence base, the preliminary nature of the analysis, and the subtlety of the effects, considerations of the global nature and population scale of the potential impact suggest that the issue warrants further attention and work. There is an urgent need to corroborate and further develop the work on performance effects of CO_2 so that the impact on human physiology and cognitive performance of different CO_2 levels in the range of 400 to 3,000 ppm, and over a much wider range of durations, can be more fully understood.

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Figures

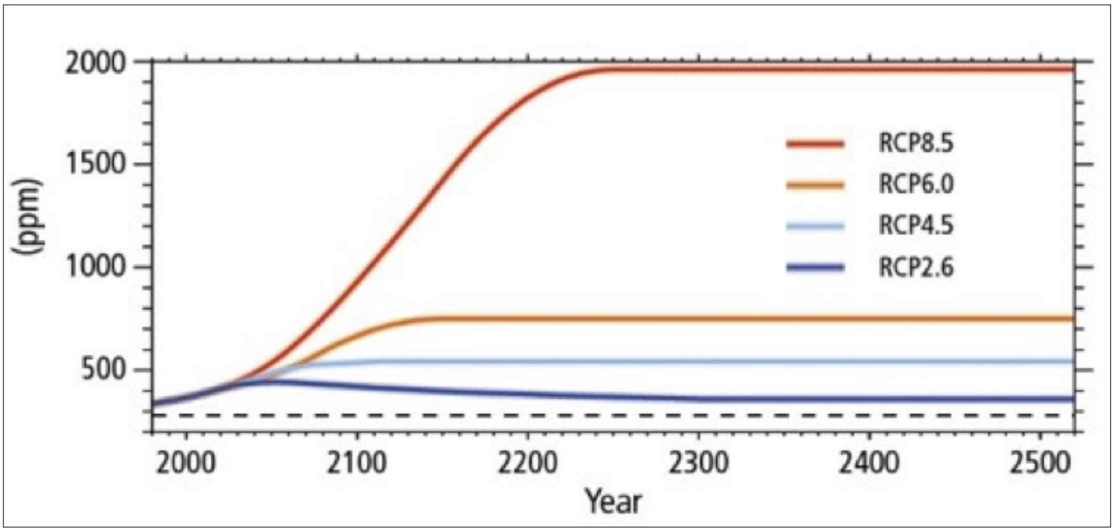

Figure 1. (Figure 2.8a in AR5 Synthesis Report). Atmospheric carbon dioxide (CO_2) […] as simulated by Earth System Models of Intermediate Complexity (EMICs) for the four Representative Concentration Pathways (RCPs) up to 2300 (relative to 1986–2005) followed by a constant (year 2300 level) radiative forcing. A 10-year smoothing was applied. The dashed line […] indicates the pre-industrial CO2 concentration.

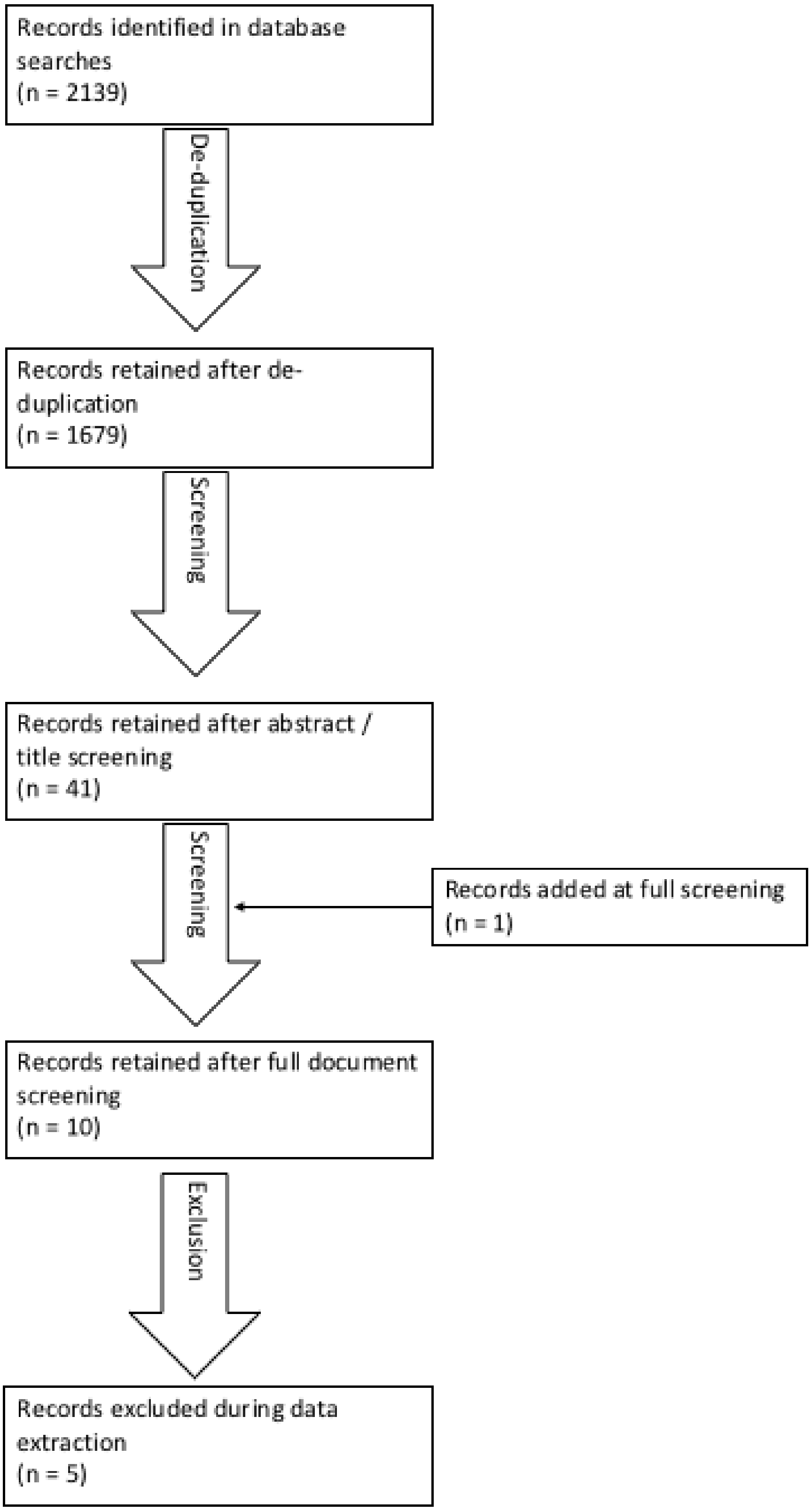

Figure 2. Flow diagram of review process.

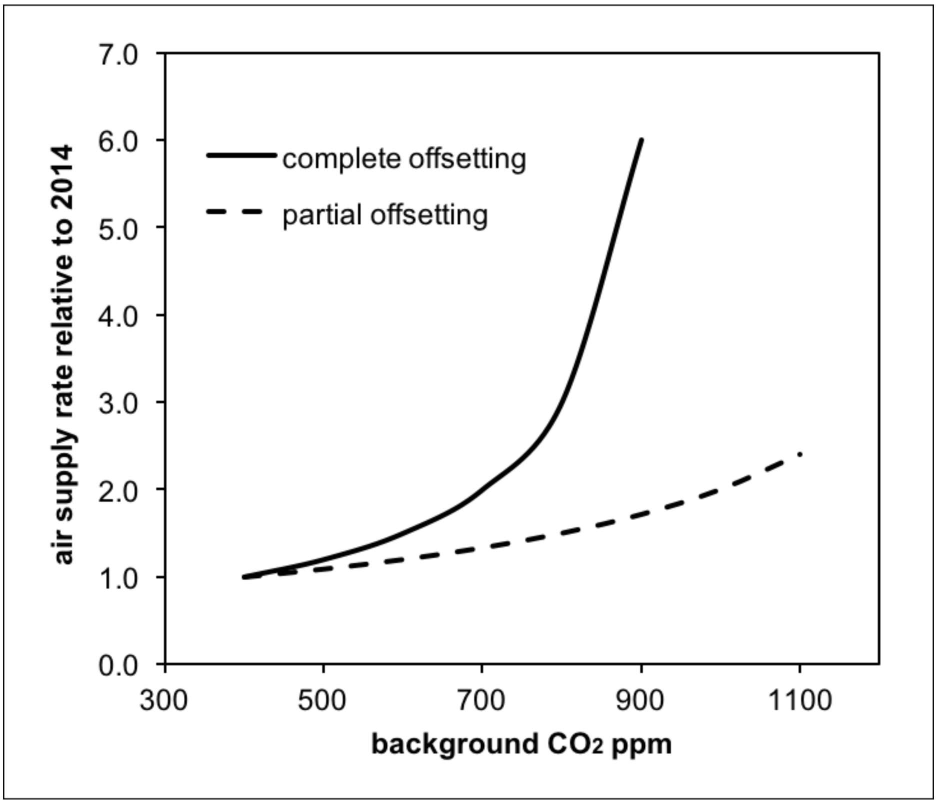

Figure 3. Two strategies for offsetting effects of increases in background CO_2 concentration on indoor CO_2 concentrations. The trajectory for complete offsetting has an asymptote at 1000 ppm, and has been truncated at 900 ppm. The partial offsetting strategy in this example assumes that half of the increase in background CO_2 is offset by larger air flows.

Tables

Table 1. Terms searched in title, abstract and keywords.

Concept	CO_2	Performance	Building
Search term	CO_2	Cognition	Indoor environment
	Carbon dioxide	Decision making	Indoors
		Performance	Office*
		Attention	School*
		Concentration	Lab*
		Memory	Building
		Task performance	Built environment

Note: * indicates a truncated term, e.g. Office* will also search for Offices, and Lab* for Laboratory.

Table 2. Key aspects of the five reviewed studies.

Paper info: first author, country, year of publication	Sample: size, type of subject, payment for participation?	CO_2 levels (ppm) and order	Exposure before testing (minutes)	Type of task	Effects
Zhang (32) Denmark 2017	N = 25 Students Yes	500, 1000, 3000 counterbalanced; on separate days.	Up to 255	Office work Neuro-behavioural tests	None
Zhang (35) Denmark 2016	N = 10 Students Yes	500, 5000 counterbalanced, exposed twice to each condition on separate days.	Up to 153	Typing Addition Connecting numbers	None
Kajtár (36) Hungary 2012	N = 10 (per experiment) Not specified Not specified	Experiment 1: 1500, 2500, 600, 5000 Experiment 2: 1500, 3000, 600, 4000 unclear whether all on same day.	Within 70, 140, and 210 mins other questionnaires were administered before mental work tasks; exact timings not specified; mental work occupied 2 or 3 periods, of 70 mins.	Proof reading Task in Experiment 2 more cognitively demanding than task in Experiment 1.	Exp 1: No Exp 2: Yes
Allen (28) USA 2016	N = 24 Professional-grade employees Yes	550, 945,1400 exposures took place on separate days.	Six hours (with 45 mins lunch break)	Strategic Management Simulation (SMS) tool	Yes
Satish(27) USA 2012	N = 22 Mainly students Yes	600, 1000, 2500 counterbalanced	≈60 minutes	Strategic Management Simulation (SMS) tool	Yes

Table 3. Rank order relationship between performance and CO_2 concentration (low, middle, high), by cognitive function.

Cognitive function	Allen et al.	Satish et al.
Basic Activity Level	low > middle > high	low > middle > high
Applied Activity Level	low > middle > high	low > middle > high
Focused Activity Level	*middle > low > high*	*high > low = middle*
Task Orientation	low > middle > high	low > middle > high
Crisis Response	low > middle > high	low > middle > high
Information Seeking	*middle > low > high*	*low = middle = high*
Information Usage	low > middle > high	low > middle > high
Breadth of Approach	low > middle > high	low > middle > high
Strategy	low > middle > high	low > middle > high

Note: *italics* indicates those cognitive functions for which the effect does not increase monotonically with CO_2 concentration.