THE MANUSCRIPT HAS BEEN PUBLISHED ON BUILDING AND ENVIRONMENT (2021)
https://doi.org/10.1016/j.buildenv.2021.107647

How Indoor Environmental Quality Affects Occupants' Cognitive Functions: A Systematic Review

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https://doi.org/10.1016/j.buildenv.2021.107647

Highlights

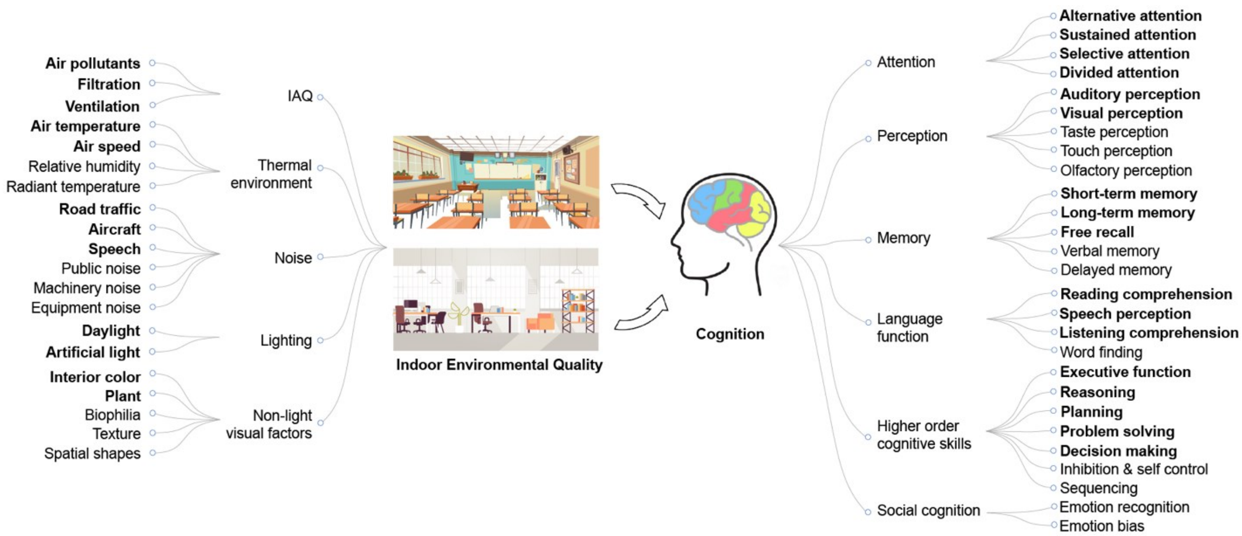
- Effects of IEQ factors on cognition are reviewed
- IEQ and cognition are but not always statistically associated
- Considerable conflicting results are identified among studies
- A specific IEQ factor may have varying effects on different cognitive functions

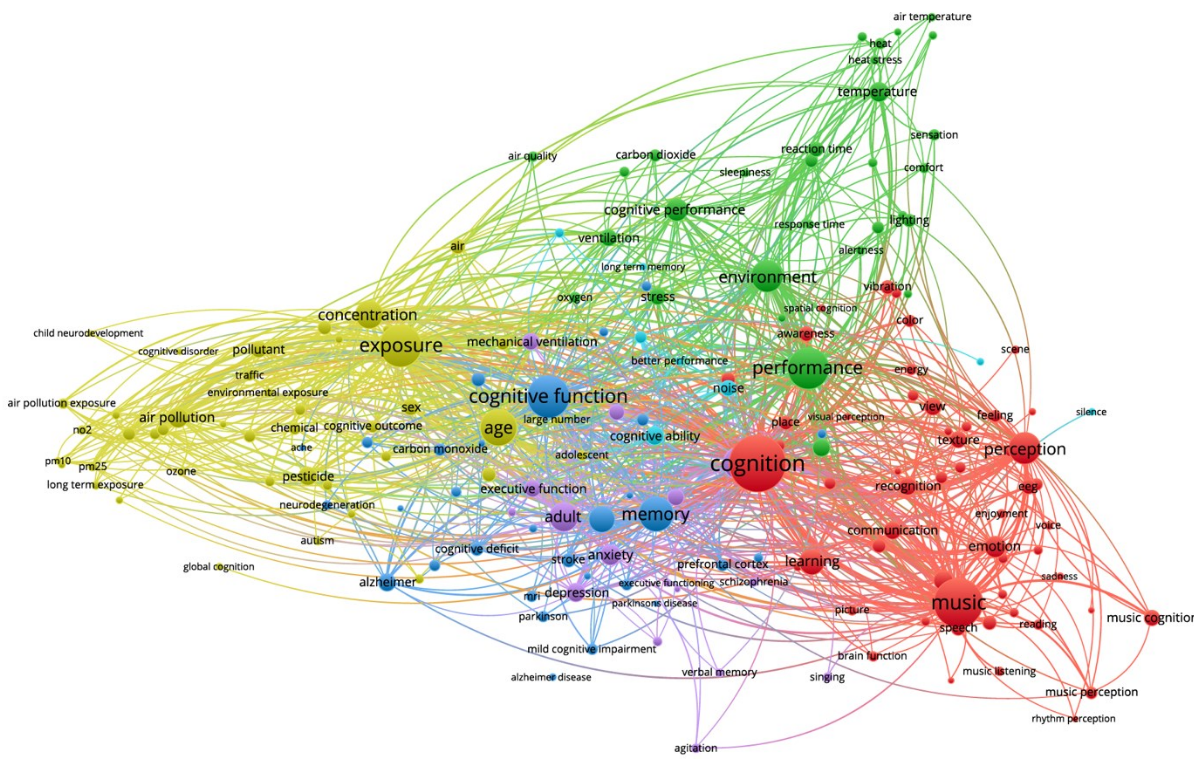
Abstract

Cognitive functions refer to the set of brain-based skills to execute tasks of various difficulty levels. As people spend substantial time indoors, the indoor environmental quality (IEQ) influences occupants' cognitive functions and consequently their learning and work performance. Previous studies have commonly examined the effects of IEQ on integrated learning or work performance, rather than specific cognitive skills. The present review decomposes IEQ into five factors—indoor air quality, the thermal environment, lighting, noise, and non-light visual factors. It divided cognition into five categories—attention, perception, memory, language function, and higher order cognitive skills—to better understand the relationship between IEQ and cognition. We conducted a detailed manual review of 66 focused studies and adopted co-occurrence analysis to generate landscapes of the associations between IEQ and cognition factors by analyzing keywords and abstracts of 8, 133 studies. Overall, results show that poor IEQ conditions are but not always associated with reduced cognition. However, the effects of a specific IEQ factor on different cognitive functions are quite distinct. Likewise, a specific cognitive function could be affected by different IEQ factors to varying degrees. Furthermore, the results suggest extensive inconsistencies in the relevant literature, especially regarding the effects of IAQ or thermal environment on cognition. Additionally, the keyword co-occurrence analysis identified more IEQ factors and cognitive functions emerging in the recent literature. Future studies are recommended to explore the factors causing the inconsistencies that we highlight here.

Keywords: *Environmental Design, Healthy Buildings, Occupant Satisfaction, Learning Performance, Productivity, Work Efficiency*

Graphical Abstract





Keyword co-occurrence of studies in the past five years (2016-2020)

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1. Introduction

Cognitive functions refer to the set of brain-based skills to required execute tasks of various difficulty levels [1]. They are associated intensively with the mechanisms of learning, remembering, reasoning, and problem-solving [2]. Each function plays an essential role in processing new information. Research in neuroscience has been stated that cognitive performance is associated with the activities of specific brain centers. For instance, the activation of frontal and parietal areas is directly associated with sustained attention performance [3].

As people now spend a substantial amount of time indoors learning and/or working, particularly in the lockdown of the pandemic, IEQ could significantly affect occupants' cognitive functions and therefore their learning and work performance. Prior reviews have [4–6] classified IEQ factors into indoor air quality (IAQ), thermal environment, light, acoustic, office and layout, biophilia and views, look and feel, and location and amenities, to name a series of the major influences.

There is a substantial body of research showing that poor indoor air quality [7], ventilation [8,9], thermal conditions [10,11], light [12], noise [13,14], and room layout [15] can profoundly degrade learning and work performance. Nevertheless, the findings of these studies, and other substantial ones on this topic [16–19], do not fundamentally differentiate between types of cognitive tasks. However, this is essential as the impacts of IEQ may vary significantly between cognitive tasks. For instance, previous research indicates that, compared with complex tasks, simple tasks, for example, might be less susceptible to environmental noise and heat [20,21]. Obviously, different learning/work tasks rely upon different cognitive functions. For instance, the presidents or chief operating officers of large corporations might require stronger skills in decision making and planning, while customer service representatives, in a call center, who handle customer complaints should be able to excel at auditory perception and emotion recognition. Similarly, reasoning skills are more involved in the process of learning mathematics compared to foreign languages. It is difficult to associate IEQ and learning or work performance without specifying each of the cognitive activities involved.

In the contemporary indoor environment, success in learning and work is mainly determined by cognitive performance as opposed to physical performance (e.g., strength, endurance, balance). Understanding the influences of various IEQ factors on each cognitive function is the key to estimating how differently a chief officer could be susceptible to poor IEQ from the vulnerability of a service representative in a call center. Unlike previous reviews that examine learning/work performance as a whole [22,23], the present study focuses on specific cognitive functions that underpin various learning/work activities, it aims to provide a multidisciplinary and comprehensive survey of research associated with cognitive functions influenced by IEQ. Another motivation is the insufficiency of qualitative and/or quantitative summaries of massive numbers of studies (in the thousands) that may not directly focus on IEQ and cognition, but still shed light on the patterns of their relationship. To fill this gap, this review work applies keyword co-occurrence analysis to extract knowledge from thousands of identified and relevant published papers.

2. Categories of IEQ factors and Cognitive functions

In this work, we synthesized a large panoply of previous reported work and grouped IEQ factors into five categories (*IAQ, thermal environment, noise, lighting, and non-light visual factors*), we just posed these with five cognitive functions into the categories (*attention, perception, memory, language function, and higher order cognitive skills*). Social cognition has been identified but not discussed in this review due to limited number of studies identified. Indoor environmental factors that do not ubiquitously exist were not explicitly considered in this review. These include transients such as music and natural-based soundscapes. However, we acknowledge that these factors may serve to improve cognition (e.g., working memory [24], verbal memory [25], spatial reasoning [26], speed of spatial processing [27]), albeit the literature is still rather equivocal concerning a number of their effects [28–32]. Additionally, this review does not consider the cognitive development of children that might be affected by IEQ [33]. Figure 1 lists the main categories and subcategories of IEQ factors and cognitive functions identified in the literature. Next section provides an overview of the basic concepts of IEQ factors and cognitive functions.

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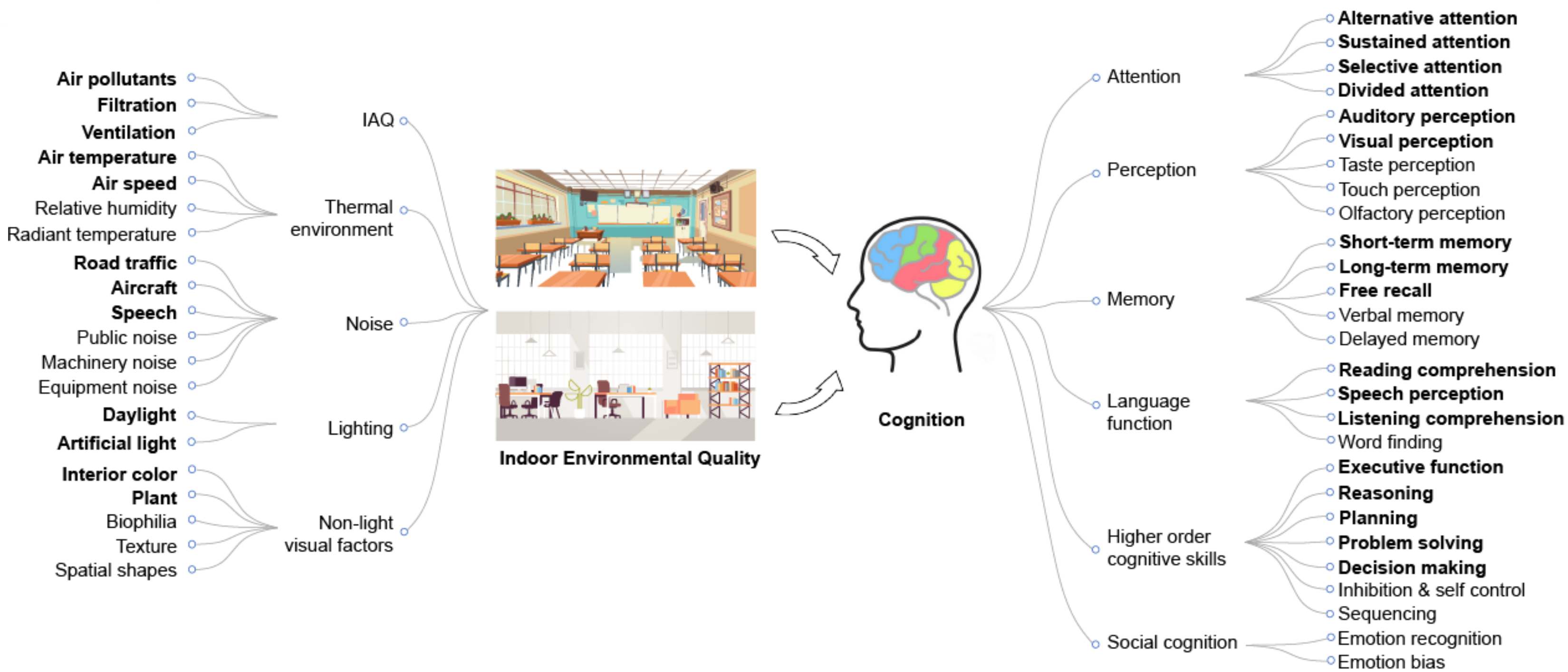

Figure 1. *Summarized categories of IEQ and cognitive functions based on the literature; The factors in bold are explicitly studied in the literature concerning the IEQ-cognition-interaction.*

2.1 Indoor Environmental Quality

2.1.1 Indoor air quality

Indoor air quality (IAQ) is a critical factor that affects both the health and productivity of space's occupants [34]. Indoor air pollutants include carbon dioxide (CO_2) [35], sulfur dioxide (SO_2) [36], nitric oxide (NO) [37], nitrogen dioxide (NO_2) [38], volatile organic compounds (VOCs) [39], semi-volatile organic compounds (SVOCs) [40], levels of particulate matter (PM) [41], biological contaminants [42,43] among many others. Practically, ventilation and indoor CO_2 concentration are used as an indicator or proxy for diverse levels of indoor air quality [44–46]. A 1000 ppm increase in CO_2 concentration decreases 0.5-0.9% of annual average daily attendance, which is equivalent to a relative 10-20% increase in student absences [47]. Each of these pollutants can influence both acts of cognition as well as rates of learning.

2.1.2 Thermal environment

Thermal environment is the physical environment that can affect heat transfer in the indoor. It influences the thermal perception of an individual and through that, the thermal comfort of occupants. Thermal comfort is the subjective evaluation of a thermal environment [48] and is mainly influenced by four physical parameters (air temperature, mean radiant temperature, air velocity, and relative humidity). These physical values are concentrated with two personal variables (clothing insulation and activity level) [48]. These go together with other factors such as gender [49], age [50,51], culture [52], exposure time [53], and physiological adaption [54]. The complexity of these influencing factors results in various prediction models, including but not limited to predicted mean vote (PMV) – a predicted percentage dissatisfaction (PPD) model [55], an adaptive thermal comfort model [53,56], and the recent personal thermal comfort [57–60] relying on machine learning principles. The thermal environment exerts fairly consistent and predictable effects on some elements of cognition, especially toward the outer bounds of tolerance [61].

2.1.3 Noise

Indoor noise can come from sources inside the building or sources external to it. Internal sources can consist of conversations of occupants [62], indoor operating equipment [63], and air distribution systems [64], while outdoor noise transmitted into indoor spaces can emanate from road traffic [65,66], aircraft [66,67], outdoor construction [68] and outdoor components of the heating, ventilation, and air conditioning (HVAC) [69]. Noise from traffic, aircraft, public, or equipment generates a complex sound assemblage that can negatively impact memory [12,70,71]. Even speech from other classrooms in school can influence students' memory in adjacent classes [72]. Occupants' perceptions are affected by both energy intensity and distribution of acoustical stimuli [73].

2.1.4 Lighting

Lighting plays a critical role in synchronizing humans' endogenous and night pacemakers with the environment. As the most powerful zeitgeber synchronizing our endogenous circadian rhythm with the environment, light has been previously described as one of the agents involved in improving cognitive performance [74]. Light quality for visual comfort is primarily characterized by photometric variables [75–77], glare [78–80], and light color temperature [81,82]. Literature regarding the effects of lighting on cognition has focused on photometric parameters (i.e., luminance, illuminance, color temperature, color rendering).

Artificial light is produced by electrical means such as lamps and light fixtures, while daylight is the combination of all direct or indirect sunlight. Daylight is considered as the best light source for color rendering and closely and unsurprisingly matches the human visual response [83]. It is a kind of trigger that motivates biological activities. Whenever possible, building design typically tries to use daylight as the source of illumination, because of its excellent color rendering provides higher satisfaction [84] and supports for stable circadian rhythms [85]. It also helps occupants to generate an active sense of pleasantness and brightness, which is positive for occupants' comfort and productivity [86,87].

The enhancement of occupants' alertness and performance can be improved by light exposure through a "non-visual" photoreception system depending on melanopsin expressing retinal ganglion cells (mRGCs) [88]. It also has been reported in recent years that human alertness, cognitive performance, and mood can be affected by non-visual lighting effects related to spectrum distribution, timing, and exposure duration, in which certain new metrics have been developed based on radiometric quantities [89–91].

2.1.5 Non-light visual factors

In addition to environment luminance, interior surface textures, spatial design, decoration, interior color, window views, biophilia, and many other non-light visual factors can influence cognition. The non-light visual factors in this review include interior color, spatial settings, closeness to natural views, and landscape. Satisfying non-light visual factors of the indoor environment positively affects occupants' cognitive function and overall performance. Humans have ingrained reactions to different colors, due to our essential relationship with nature. For example, the color green reminds us of an environment that makes us feel calm and harmonious [92]. Also, indoor visual interests and opportunities for discovery provide intellectual and cognitive stimulation, which have been found to foster creative behaviors [93]. Such factors have been considered influential in restoring attentional resources, as we articulate further below.

Humans tend to seek connections with nature and other living things, as posited by the biophilia hypothesis [94]. Natural environments have, as we have noted a restorative effect on attention, according to the attention restoration theory (ART) [95]. A view of natural elements is beneficial for high workability and job satisfaction [96]. With respect to the visible features of outdoor or indoor space, landscapes with natural features have a positive effect on cognition and performance. High school landscapes that lack natural features have been shown to reduce standardized test scores [97], while landscapes with greater tree coverage ratios show a higher percentage of proficiency or advancement in reading and mathematics [98].

2.2 Cognitive functions

Cognitive functions can be summarized using a number of different taxonomies. Prior review work on cognition and human performance has classified cognitive functions into attention, memory, perceptual-motor performance, judgment, and decision making [2]; while [99] categorized it into perceptual functions, memory, thinking, and expressive functions. Another categorization approach to cognition consists of memory, attention, reasoning, visual perception, language function, problem-solving, and planning [100]. Among the cognitive functions reported in the studies we have examined, attention, perception, memory, language function, and higher order cognitive skills are the most commonly studied when considering associations with IEQ. Each cognitive function can be further sub-divided as described in Figure 1. For instance, the higher order cognitive skills consist of problem solving, decision making, reasoning, and others [101]. Other essential cognitions (e.g., social cognition) are also listed (in the unbolded text) but not studied in this current review.

2.2.1 Attention

Attention is an individual's ability to concentrate on a particular facet of information [102]. Attentional processes can be further categorized as sustained attention [103–105], selective attention [106–109], and divided attention [110–112]. Attentional performance can be assessed using the Continuous Performance Task (CPT) [113], reaction time [114], Stroop tasks [115], the attention network test [116], and the dot-probe task [107] among others. For instance, reaction time is the assessment of motor and mental response speeds, as well as measures of movement time [117,118]. It is also an important performance measure of multiple cognitive functions beyond attention [119], such as sensory memory [120].

Attention has a limited capacity. People cannot easily focus on more than one stimulus at a time, unless experience with the task that has enabled automatic processing [121]. Also, a person might possess an attentional bias that refers to the tendency of that individual to selectively attending to a certain category of stimuli in the environment while tending to overlook, ignore, or disregard other kinds of stimuli [122]. Attentional bias can be influenced by emotion and mood [123,124], and these moderating effects may confound the association between IEQ and attention. Moreover, attention could be diverted from stimuli to be remembered by environmental proximal stimuli (e.g., conversation in an open-space)[125], making it vulnerable to indoor environmental factors.

2.2.2 Perception

Perception refers to the set of cognitive processes to capture, organize, identify, and interpret the stimuli received by the sensory organs to understand the presented information in the environment [126]. It acts as an essential cognitive ability in our lives to connect us with the surrounding world. While some reports such as [127,128] distinguish perception from cognition, numerous researchers regard perception as an aspect of overall cognition [129,130]. Perception is different from sensation. The sensation is the process of detecting our environment, while perception is the interpretation of what is sensed. Perception is more involved with top-down processing which itself is influenced by an individual's expectations and knowledge rather than simply by the stimulus itself [131].

Perception may be biased as a function of emotion [132], individual differences (such as different sensitivity to tone sequences [133]), personal context [134], beliefs, and expectations [135] that might confound the influence of IEQ on perception. For instance, a person's perception of thermal comfort might be affected by the opinion of another person sharing the same office.

There are multiple modes of perception: auditory perception [136], visual perception [137], speech perception (also a language function), taste perception [138], touch/haptic perception [139], and olfactory perception [140]. Visual perception is the primary human sense that moderates surrounding information received by the eyes [141]. Ref [142] concludes that visual perception is efficient in getting information associated most especially with dynamic variations. Visual stimuli can be affected by people's motivational state [143]. For instance, humans' motivation can influence the optical system to indicate the content of conscious perception. Speech perception has a more specific scope than general auditory perception, which refers solely to the ability to receive and interpret information received by the ear and interpreted by specific language cells in the brain.

2.2.3 Memory

Memory is a function that allows the brain to encode, store, acquire, and retrieve knowledge as needed [144]. It is a crucial element of cognition that helps us identify who we are, gain new knowledge, and form a continuity of conscious experience [131,145]. Memory is a component of the information processing system with both explicit and implicit functions [131]. Explicit memory refers to instances of conscious recollection, such as a response to a direct request for information about one's past. Implicit memory deals with cases when people are asked to perform some tasks without the use of declarative knowledge [146]. The memory could be subdivided into as many as 256 different categories [147], going from abnormal memory, through terms such as diencephalic memory, and on to rote memory and sensory memory, and finally to working memory [146]. However, we mainly focus here on broad categories of short-term memory (STM) and long-term memory (LTM) [149].

External stimuli can be converted to memorized information via roughly three steps [150]. First, human beings process stimuli through sensory memory that serves as a brief holding system for the information presented to various sensory systems [151]. Sensory memory is vital for the listener to integrate incoming acoustic information [120]. Then, the working memory processor encodes the information, keeps it in mind temporarily, and meanwhile searches and activates data from previously-stored memories [152]. Finally, the new information is integrated with and then stored in long-term memory [153].

STM is versatile and supports reasoning and the guidance of decision-making behaviors [154]. When a person is distracted (e.g., by indoor noise or experiencing a cold draft near an exterior window), information can be rapidly lost from such informative storage. A more modern conceptualization of STM is working memory, which is a term for the type of memory holding information for short periods while being manipulated [155]. Working memory involves the processing of information (such as solving simple arithmetic problems while also remembering given words during span tasks) as well as the executive control of attention. Besides, sensory memories, as a type of STM, are the brief holding system for the information presented to the various sensory systems. Information is thought to be held briefly in each system as it waits for further processing [151]. Sensory memory is, for example, a vital part of the listener to integrate incoming acoustic information [120].

LTM is a vast store of knowledge and a record of prior events. Long-term memory also possesses a lot of subtypes. Distinctions by type of material and mode of presentation include verbal memory, visual/spatial memory, and olfactory memory, together with procedural memory (also called kinesthetic or motor skill memory). Another set of distinctions, in terms of types of declarative (or explicit) memory, are episodic memory, autobiographical memory, and semantic memory [146]. LTM has a much larger capacity and duration than STM. As such, LTM may be less susceptible to poor indoor environmental quality.

2.2.4 Language function

Language function involves a set of cognitive skills that enable an individual to effectively understand and generate language for effective interpersonal communication [156]. It can be divided into five components, semantics, phonology, morphology, syntax, and pragmatics [157]. Language acquisition is the process by which humans perceive, comprehend, and acquire information from language [158]. Some examples of language functions include word finding, language comprehension, repetition, expression, reading, and writing [158]. Memory, attention, and individual differences are common factors that affect reading and writing abilities. As a function of language acquisition, speech perception is the process that employs sensory functions to hear, and then interpret and understand the sounds [159,160].

Speech perception is an integrated result of the recipient's memory, attention, and both passive and active receipt of signals. The phenomena of short-term memory deficit are common for children who are poor readers [161]. Speaker’s lip movements act as visual stimuli that affect the auditory perception of what is said. This process is most apparent when there is a combination of acoustic information and visual information for a bilabial utterance combined [162]. A perception study [161] proved that poor readers have a perceptual difficulty with speech perception due to the material-specific problem. Illusions can also be generated when aural perception becomes subordinate to what the listener believes they see in the expression of the speaker’s lips.

2.2.5 Higher Order Cognitive Skills

Higher order cognition is a multi-faceted and complex area of research that refers collectively to the mental processes of reasoning, conceptualization, critical thinking, decision making, and creativity. Higher order cognition involves the ability to understand and implement the steps necessary to solve problems, establish new areas of learning, and think creatively [163]. Primary topics investigated in higher order cognition consists of executive function, reasoning, planning, and problem solving.

These executive functions are a set of complex cognitive processes that help people manage thought, skills, and necessary behavior, and action to achieve goals [164]. They are diverse, correlated, and overlapping. People need these functions to execute goal-oriented behaviors, such as managing time, focusing on a task, planning, and organizing. The basic executive functions can involve cognitive inhibition, cognitive flexibility, and emotional control, while reasoning, planning, problem-solving, and decision making remain higher-order executive functions with the requirement of several more fundamentally processes working at the same time to support them [165,166].

Reasoning is regarded as the cognitive process that solves a problem by establishing logical relationships between different problem elements [167]. It is the central activity in intelligent thinking. General reasoning skills include inferential reasoning, deductive reasoning, analogical reasoning, conditional reasoning, and automated reasoning [168]. Reasoning ability can vary by gender, age, and are affected by the surrounding environments including IEQ [169–171].

People use planning skills to set and achieve goals by developing plans and choosing the appropriate actions based on the anticipation of consequences [172]. Planning is key in the ability to make shifts in attention. It is also a vital process for decision making, self-control, and self-monitoring. Age and gender can be related to differences in planning performance [173]. In one study younger adults usually made quicker and fewer inappropriate planning moves than older adults. And girls with the ages of 5 and 17 years have been documented to outperformed boys at the same age on certain measures of planning [174].

Problem solving is an integrated skill to generate and select solutions for problems. It is related to mental strategies and heuristics as well as physical health [166]. Previous research found that indoor environmental factors such as lighting, noise, or thermal environment have established effects on problem solving [12,169,175]. Other higher order cognitive skills could consist of judgment and decision making that is the cognitive ability to do a selection among several possible alternatives [176].

3. Methods

In order to establish systematic effects of IEQ on these orders of cognitive performance, we conducted a thorough search of the related scientific literature using two methods, a conventional manual review and keyword co-occurrence analysis. The conventional manual review focused on the most relevant studies about the explicit association between specific IEQ factors and cognitive functions. The experimental setup, assessment tools, and the major results were tabulated in detail after scrutinizing each study. Although arduous and time-consuming, the approach provides an avenue to meticulously analyze results and serves as one of the most commonly used methods in review studies [177,178]. There are thousands of studies in the literature involving IEQ and/or cognition that have only implicitly addressed these same associations. The information in these studies, though not providing direct evidence-informed decisions, can still shed much light on the association between IEQ and cognition. Such information can be revealed through the keyword co-occurrence analysis which we have provided here.

3.1 Conventional manual review

We searched and then gathered the most relevant studies that specifically and explicitly examined the relationship between IEQ and cognition. These were derived from multiple sources, including scientific journals, conference proceedings, and relevant books. The searched databases consisted of Google Scholar, ScienceDirect, Springer, National Center for Biotechnology Information (NCBI), the American Society of Heating, Refrigerating, and Air-conditioning Engineers (ASHRAE), and the Proceedings of Indoor Air and Healthy Buildings conferences.

Keywords

We first searched the following keywords, *cognitive performance, performance tasks, cognitive function, productivity, attention, perception, memory, language function, and higher order* *cognitive skills* for cognition, while using *IAQ, ventilation, thermal environment, noise, lighting, and non-light visual factors* for IEQ factors. We then conducted a follow-up round of searching for relevant studies by examining the reference lists of each of these collected studies.

Inclusion and exclusion criteria

We refined the papers selected based on the following rules. First, for laboratory studies, experiments had to have been conducted in well-controlled climate rooms or chambers; for field studies, environmental factors had to be clearly described and quantified. Studies without quantitative measurements of IEQ factors were excluded. Studies that did not carry out cognitive performance tests in different IEQ conditions or report performance test results with statistical analyses were excluded in the review. Third, we limited the search to concrete cognitive functions; namely, attention, perception, memory, language function, and higher order cognitive skills. Performance tests that could be mapped into these five cognitive functions were included here. Performance tests that did not fall into the above categories or integrated test kits combining various cognitive functions without reporting individual scores for each function were also excluded. Table A1 in Appendix I summarizes the cognitive tasks corresponding to different cognitive functions.

Levels of Association between IEQ and cognition

A preliminary review showed a number of conflicting results for the effects of IEQ factors on cognition. Some studies reported a statistically significant association (either positive or negative association); while some reported no clear association between the two. Yet others reported mixed results of positive associations, no associations and/or negative associations in different tests or participant categories. To demonstrate the overall quantitative relationship between IEQ factors and cognition, we, therefore, categorized levels of the statistical association between IEQ factors and cognition into three ordinal levels ranging between 0 and 2. Here, **"0"** refers to *no statistical association between IEQ and cognition*, meaning that the tested cognitive function was not significantly different between tested IEQ conditions ($p > 0.05$). A degraded **"1"** denoted *mixed association*, in which varying levels of statistical association were reported in different performance tests and/or participant groups; A score of **"2"** referred to *statistical associations*, where consistent positive or negative statistical association ($p < 0.05$) was reported between IEQ and cognition. We applied "N/A" to denote the significance level if a study did not report p values. An assigned score indicates an ordering of the association level.

3.2 Keyword Co-occurrence Analysis

As a particular form of data mining, text mining focuses on handling unstructured or semi-structured datasets, such as that represented by text documents [179]. It is a well-established practice that is commonly used to extract patterns and non-trivial knowledge from documents written in a natural language [180]. In this review, keyword co-occurrence analysis was applied to assist in literature reviews in retrieving information from large-scale data that is usually too big to handle manually. Using the method, we were able to retrieve information from unstructured text and visualize distilled knowledge in a concise form [181]. We first identified 8,133 studies that mentioned both IEQ and cognition in their abstracts and/or keywords using the following search logic on Scopus.

(cognition OR "cognitive function*)*
AND
("air pollution" OR "air filtration" OR ventilation OR Radon OR "particulate matter" OR PM10 OR PM2.5 OR "black carbon" OR aerosols OR voc OR "volatile organic compound" OR ozone OR O3 OR asbestos OR pollutant OR "carbon monoxide" OR "carbon dioxide" OR CO2 OR formaldehyde OR NO2 OR "nitrogen dioxide" OR pesticide OR moisture OR "indoor microorganism" OR "air odor" OR molds OR combustion OR "room temperature" OR "air temperature" OR "air speed" OR "air velocity" OR "relative humidity" OR "thermal comfort" OR "heat stress" OR "radiant temperature" OR "room NEAR/15 noise" OR "traffic noise" OR "airplane noise" OR "speech noise" OR "public noise" OR "machinery noise" OR "equipment noise" OR music OR lighting OR daylight OR "artificial light" OR "visual comfort" OR biophilia OR texture OR "spatial shapes" OR glare OR "room NEAR/15 plant" OR greenery OR glare OR "indoor layout" OR furniture OR furnishing OR "window view" OR "wall color" OR "interior design" OR "building material" OR vibration)

Then we applied the VOSviewer (visualization of similarities) [182] to construct bibliometric landscapes that extract a holistic relationship between IEQ and cognition from substantial bibliographical data (keywords and abstract). The tool provided the visualization of co-occurrences of scientific topics. For instance, ventilation is highly related to indoor air quality. Also, through co-occurrence keyword analysis of studies at different periods, we were able to identify emerging topics in the field.

4. Results

We synthesized the research findings on the influence of IEQ on attention, perception, memory, language function, and higher order cognitive skills using the conventional manual review of 66 studies and the co-occurrence analysis of keywords and abstracts of 8,133 studies. The experimental setups and major results of the reviewed studies are summarized in Appendix I Table A2-A6. Each of these tables summarizes the key findings between one specific cognitive function and IEQ factors. The table also includes sample size, environmental conditions, and metrics to evaluate cognitive functions. Please note some studies appear in multiple tables since they have investigated more than one cognitive function. This section summarizes the major findings of Appendix I Table A2-A6 and insights from the co-occurrence analysis.

4.1 Relationships identified with a conventional manual review

4.1.1 IEQ's Effects on Attention

The reviewed studies in Appendix I Table A2 revealed that most IEQ factors, when at disrupting levels of values, negatively influenced attention in general. However, there is also present evidence showing that some perceived adverse environments might even elevate attentional or concentration. For instance, several studies reported enhanced working attention [12] and concentration performance [170] due to increased temperature and noise levels, respectively.

Indoor Air Quality

Air pollutants negatively impact the neurocognitive functions of occupants during work or learning processes. Increased levels of annual ozone and particulate matter was related to a decrease in cognitive performance [183,184]. An increase of 10 ppb in ozone concentration caused a 5.3 years' age-related decline in attentional performance [184]. Higher black carbon (BC) levels had a positive association with increased errors of commission and slower hit reaction time (HRT), as well as mean reaction time for all target responses [185], but the absolute relationship between pollutant concentration and attention performance was not significant ($p > 0.05$). Traffic pollution exposure for adolescents showed an inverse association with their sustained attention and may therefore assumedly undermine neurobehavioral functions [186].

As an indicator of indoor air quality, CO_2 has recently been identified as an indoor pollutant due to its potential effect on cognitive function [35]. A field study in a primary school concluded that children showed significantly poorer concentrate levels on the courses when the level of CO_2 in classrooms was high [8]. The increased levels of CO_2 led to an approximately 5% decrement on attentional performance, as reported by the study. Nevertheless, other studies showed little influence of CO_2 level on attention [187,188] Elevated CO_2 concentration in the classrooms did not reduce students' global short-term attention, although a decrease in the secondary outcome accuracy (e.g. the total number of characters processed) was found for students exposed to poor air quality [187]. Ref [188] argued that it might be the bio-effluents, rather than pure CO_2 level, that reduced cognitive performance. Another study employing physiological and neurophysiological monitoring also reported no effect of CO_2 on attention performance [189]. A critical review of the area concluded that pure CO_2 only consistently affects high-level decision-making performance [190].

Elevated indoor CO_2 concentration is primarily derived from insufficient ventilation. Previous studies have reported improvements in students' working memory and attention in primary school buildings at higher ventilation rates [191]. Ref [192] identified a 2.2% improvement in attentional performance during these higher ventilation rates.

Thermal Environment

Prior studies have shown that attention can be strongly influenced by the thermal environment, although the direction and magnitude of influence may not be always consistent. Under steady-state conditions, the attention index of 117 high-school students decreased when they were thermally uncomfortable [193]. Participants had the highest performance test score at 26 °C compared with at either 23 °C or 29 °C when a personally controlled fan was available to use [118]. Under thermal transients in Ref [170], concentration performance was significantly and positively correlated with the rate of temperature increment ($p < 0.05$) in temperature cycles starting from 22 °C. This implies increased concentration performance when the temperature rises quickly. But a separate study [194] indicated opposite results that subjects had a better attentional performance at 16 °C compared to results at 26 °C and 36 °C. Attention tested by using the cursor positioning test indicated no significant difference in the subjects' performance in three different thermal environments [195]. There was also no significant difference of attention in a study [196] which used a star count test in two temperature conditions of 23 °C and 29 °C. Attention, as assessed by

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the Stroop test without feedback, was significantly different between 23 °C and 27 °C [197]. However, the difference was not significant when feedback was provided to the participants. These sorts of results confirm that at ambient temperature, close to setting, and individual capacities each exert impactful influences on outcome.

Noise

The influence of noise on attention is also complicated. High school students worked faster with high ventilation noise but only at the cost of less accuracy [12]. The results supported a speed-accuracy trade-off hypothesis that decisions are made slowly with high accuracy or fast with a high error [198–200], contingent upon acoustic surround. Age is a confounding factor when considering the influence of noise on attention. Elderly people may be more vulnerable to noise. Listening to speech with multi-talker babble noise, such as in a crowded office, reduces activation in the auditory cortex but increases memory and attention-related cortical areas (prefrontal and precuneus regions) for older people [201]. However, noise exposure apparently has little significant influence on students' attention performance, at least to a reasonable threshold value [71,202].

Lighting

The literature has recorded controversial findings as to know if attention is affected by lighting. The correlated color temperature of 4,300 K resulted in the best-sustained attention performance for undergraduates using the Chu Attention Test. Also, sustained attention was more affected by lighting in females than male students [203]. Increasing illuminance from 200 lux to 1500 lux promoted attention when the room air temperature was 22 °C. But the opposite trend was found at 37 °C. This implies an interactive influence between thermal and visual comfort [204]. A dynamic lighting system that adjusted lighting color and brightness of computer screens significantly improved target spotting time in a computer game for both casual gamers and non-gamers [205]. However, the effects of lighting on attention have not been found in other studies. Neither light color temperature nor lighting intensity influenced the concentration of third-grade children [206]. For example, sustained attention was also independent of lighting conditions for older adults who were night shift workers [207].

Non-Light Visual Factors

Fisher et al. [208] investigated how classroom decoration affected the ability of children to concentrate on lesson content. Children were more distracted by highly decorated environments, spent more time on the task, and gained less knowledge when compared with a relatively plainly decorated classroom. Colors can stimulate an individual's physiological and emotional responses for focal attention and thereby facilitate learning. Pale colors were rated more positively than vivid ones, due to feeling more calm and relaxed [109, 214]. Additionally, biophilic environments can promote the attention of occupants. Students' views of nature or buildings is another factor influencing attention. Both outdoor natural views [210] and indoor views of plants were reported to promote students' attention [211]. In other words, indoor and outdoor visible greenery increases the ability to concentrate and reduces stress [217, 218]. Significantly better performance of participants' attention was reported when a window view is available than when it is unavailable [214].

https://doi.org/10.1016/j.buildenv.2021.107647

4.1.2 IEQ's Effects on Perception

We summarized in Appendix I Table A3 the major findings as to how IEQ affects perception. Overall, the accumulated knowledge reports studies focusing on auditory perception and visual perception. Noise and poor lighting are common stressors for perception.

In a visual search task, participants showed a significantly different performance, normalized by mental workload, between warm and neutral conditions, and between warm and cool conditions [215]. Survey results by Ref [216] demonstrated that façade design affected occupants' perceived control over their environments. Uncomfortable environments are through to generate perceptions of stress and negative attributions about performance [217].

Lee et al. [218] examined the combined effects of color temperature and illuminance in the office on the visual perception of occupants. They concluded that the less than subjects were visually disturbed by light during tasks, the more visual comfort they felt. Lighting also affects the perception of facial surfaces [219]. Observers' ability to recognize and match faces and objects was higher for top lighting on the objects than bottom lighting. Berman's theory [220] states that elevated color temperature, associated with smaller pupil size can enhance visual acuity. In this same vein, the performance of a visual perception task on color recognition is higher with the lighting of higher color temperatures [221].

The negative effects of noise exposure on performance could be attributed, at least in part, to "learned helplessness", which is a syndrome of defeat typically resulting from exposure to uncontrollable circumstances [222]. Occupants might perceive noise to be uncontrollable or have little perceived control. A socio-acoustic survey observing perceived control over aircraft noise correlated negatively with identified effects of noise (e.g., disturbances of reading and sleep). This supports the claim that "learned helplessness" contributes to the effects of noise exposure. In terms of specifics, the linear exposure-effect association was identified between exposure to chronic aircraft noise and impaired reading comprehension [71].

4.1.3 IEQ's Effects on Memory

Appendix I Table A4 catalogs the major findings regarding the impairment of memory due to poor IEQ. Our review here demonstrated that short-term memory and working memory are most investigated by previous studies via recall tasks. Overall, results show that memory is generally associated with most IEQ factors.

Indoor Air Quality

The cross-sectional association between fine particulate concentration levels and cognitive function in older adults has identified that a higher air pollutant concentration leads to significantly reduced levels of working memory [223,224]. The incident rate of errors on tests of working memory shows a ratio of 1.53 with a 10 $\mu g/m^3$ increase in $PM_{2.5}$ concentration [223]. Each 10 ppb increase in annual ozone was associated with decreased short-term memory, equivalent to 5.3 years of aging-related decline in cognitive performance [184].

https://doi.org/10.1016/j.buildenv.2021.107647

Students showed 8% higher picture memory with an increased room ventilation rate that was associated with lower CO_2 levels [192]. Strategic management simulations [9,35,225] were applied to investigate how indoor CO_2 influenced cognitive performance, but its effects on memory were not reported as the tools were more predictive in domains such as strategy, information usage, and crisis response. However, the effects of elevated CO_2 concentrations on memory performance were not consistent in some other studies. Neither response time nor accuracy of a picture recognition task was significantly compromised at approximately 2,900 ppm when compared with 690 ppm [119]. A similar conclusion was reported for CO_2 at 2,700 ppm versus 700 ppm [189]. Zhang et al. [188] also did not find any statistical significance in digit span memory scores under bioeffluents or pure CO_2. On the other hand, external oxygen administration was found to improve memory formation in the first place [226–228]. Inhalation of oxygen immediately before learning a word list increased the average number of words recalled some 10 minutes later [226]. Inhalation of 100% oxygen for a short time enhanced the memory for names and faces [228]. These findings, however, were not replicated by other studies that focused more on long-term memory [229,230].

Thermal Environment

The reviewed studies on the effect of thermal environment on memory performance do not report consistent relationships between the two entities. The extended-U model suggests that memory performance will remain stable across a broad range but rapidly deteriorates at the thermal extremes [236, 237]. Students showed the best memory performance when the air temperature was between 22 °C and 26 °C [10]. Even while exposed to 43.3/27.8 °C (dry/wet bulb temperature), the short-memory performance for university students did not change significantly, as compared to a more comfortable condition of 26.7/17.2 °C (dry/wet bulb temperature) [233]. Poorer short-memory by recalling word lists did occur at 48.9/31.1 °C (dry/wet bulb temperature). Similarly, the average recall performance did not drop significantly when the chamber air temperature was between 16.7 and 32.2 °C but did so between 32.2 to 35 °C as individuals began to approach integrable levels [233]. Zhang and de Dear [170] reported no significant correlation between thermal environment and memory performance in six temperature cycles. College students exposed to 25.5 °C, 28 °C and 33 °C did not demonstrate significant memory changes using a positioning test and letter search test [195]. Neither working memory performance nor long-term memory performance was significantly impaired when the temperature, was raised from 23 °C to 29 °C [196].

Contradictory results were also reported in the literature regarding the influence of mild temperature on memory performance. Working memory measured via a forward digit span test dropped at slightly cooler (21.7 °C) and warmer conditions (28.6 °C) from the neutral condition (25.2 °C) [215]. Nevertheless, significant reduction only occurred for the hard version of the task but not the easy one [234], which suggests an interaction with task type. Regression analysis by Cui et al. [10] showed that long-term memory performance peaked ($p < 0.01$) at 26 °C in the temperature range of 22 °C to 32 °C.

The influence on memory due to cooling might not be equivalent to that of heating. Elevated body core temperatures from 36.6-37.4 °C to 38.8-39.1 °C did not affect memory registration or the immediate ability to recall digit spans [235], but reduced body core temperatures from 36.7 °C to 34-35°C did induce a loss of approximately 70% of data that could normally be retained from a memory test [236]. In addition, memory performance in temperature cycles ranging between 21.3 and 31.2 °C was significantly higher than temperature cycles starting from a slightly higher temperature (23.0-31.5 °C) [170]. The performance of a digital span test increased by 2.8% when reducing the temperature from 27 °C to 23 °C [197]. However, this increase did not prove statistically significant.

Noise

Noise was reported as an environmental stressor that impacted memory in many studies [20, 72, 73, 242]. Noise hinders recall and recognition in student learning. Poor listening conditions due to background noise and/or long reverberation times, impair memory and learning, even if students could hear what was said by an instructor [72]. Traffic noise can also worsen performance in both a search task and a memory task [238]. Stansfeld et al. [71] identified a linear association between exposure to chronic aircraft noise and impairment of recognition memory through the assessing 2,844 children aged 9 to 10 years. Both intentional and incidental memory were affected by chronic noise exposure, and school children who were chronically exposed to noise were found subsequently to be worse at recognition memory, as reported in Ref [202].

Memory involved in complex tasks has proven to be more susceptible to noise compared to that of simple tasks [20, 244]. In addition to task complexity, one type of noise might be more harmful than another to memory, especially intermittent noise. Two experiments revealed that background speech was more detrimental to prose memory than aircraft noise [71, 245]. Furthermore, there might be interaction effects between noise and illumination on memory. Subjects' short-term and long-term memory recall was found to vary with combinations of ventilation noise and illuminance levels [12, 246]. Interactions were also found between noise and heat on the long-term recall of a text [12].

Lighting

Long-term memory was enhanced when individuals are exposed to a light color temperature that induced a less negative mood [169]. The combination of color temperature and illuminance that best preserved a positive mood increased performance in free recall tasks. Cool-white lighting impaired the long-term memory recall of a novel text when compared to warm-white lighting [241]. However, the influence of blue-enriched classroom lighting on short-term encoding and retrieval of memories was not found for high school students [74]. No interactive effects on memory were reported between light and noise [241], but interaction was found between gender and light color temperature on mood and long-term memory [169,242].

Non-light Visual Factors

Exposure to green space has beneficial effects on the development of working memory for primary school children [33] and thus access to these green spaces was associated with improved memory [243]. Ko et al. [214] reported that Window views influenced different memory associated with various levels of significance. The working memory test score of the participants in a room with a window view was 6% higher ($p < 0.009$) than that in a windowless room. However, no significant difference was identified for short-term memory by the study. Participants with a major depressive disorder performed better on memory span tests after walking through a green arboretum, relative to traffic-heavy streets lined with university and office buildings [244].

4.1.4 IEQ's Effects on Language Functions

Appendix I Table A5 catalogs the effects of IEQ on language functioning in terms of capacities, such as reading and writing. Ref [245] investigated whether the combined environmental factors of light, sound, and temperature in a classroom affected student performance during listening and reading tasks. It was reported that indoor sound and temperature had a greater negative influence on students' listening and reading tasks when they were outside the comfort zone. However, the modeled association between reading test scores and ventilation rate did not show any statistical significance in another preliminary study [246]. The conditions of artificial light were found to influence the students' reading performance [206]. It was revealed that "focus" lighting consisting of 1,000 lux illumination and 6500 K color temperature significantly increased students' oral reading fluency compared to a "normal" or baseline lighting condition (500 lux with 3,500 K).

Noise effects on recall and recognition are significant [247]. Item difficulty, position, and ability were not found to interact with these noise effects in the study. Neither did arousal, distraction, perceived effort, or perceived difficulty in reading and learning mediate the effects on recall and recognition. Anderson et al. [248] showed that background noise usually disrupts neural timing and challenging listening conditions disrupted the inability of speech perception. Ref [249] identified significant effects of reverberation on speech perception of spoken items in classrooms. Outside noise influences language fluency, which acts as the bridge between sound source and comprehension [250]. Children's speech perception and listening comprehension can be significantly impaired by background speech [251]. Irrelevant speech has a significant influence on participants' reading comprehension [252]. Speech recognition was not only influenced by speech-to-noise ratios (SNRs), but also by thermal conditions as well [253]. Moreover, Wong et al. [201] reported that age confounds the relationship between noise exposure and speech perception. Compared to adults, children are more impaired by detrimental listening conditions. Older adults, who experience reduced activation in the auditory cortex, have increased activation in attention-related cortical areas. Age and hearing loss were both related to less release from the effort when increasing the intelligibility of speech in noise, as identified in the same study.

Non-light visual factors also affect language functions such as reading [209]. The color in a private space affects students' learning, as well as physiological and emotional states. Vivid colors are beneficial for students' reading, while blue is better for relaxation and calmness.

4.1.5 IEQ's Effects on Higher Order Cognitive Skills

The listed studies in Appendix I Table A6 describe the association between indoor environmental factors and different forms of higher order cognitive skills. In general, poor IEQ conditions were reported to have negative effects on these higher order cognitive skills, but to varying degrees. However, some studies have found no significant association between IEQ factors and higher order cognitive skills.

Indoor Air Quality

Occupants' performance, which was assessed using, but the speed of addition, response time in a redirection task, and the error rate of tasks, was reduced when participants were exposed to an elevated level of CO_2 together with bio effluents [188]. The adverse consequence due to high CO_2 levels includes the impairment of decision-making performance [35]. Also, the increased response time has been related to ozone exposure [184]. NO_x showed an association with a decline in the cognitive test scores for visuo-construction, which involves the ability to organize and manipulate spatial information [254]. An epidemiologic study, using 789 elderly women who attended a medical examination in 2007-2009 supported the proposition that lower scores in reasoning were correlated to particulate air pollution [255].

Thermal environment

Thermal comfort plays an important role in the higher order cognitive skills. A warm environment can be associated with reduced reaction time. Participants performed tasks more rapidly at 32 °C compared to other conditions (27, 24, and 19 °C) [99]. This phenomenon was explained by postulating that participants wanted to finish tasks quickly in the uncomfortable thermal environments, or that they were activated by elevated internal body temperature [256]. Another study also reported increased task speed as the temperature ascended [235]. However, findings were not consistent overall in the literature. For example, a study found that compared to a cooler temperature of 23 °C or warmer temperature of 29 °C, subjects had the fastest processing speed at 26 °C [118]. This study suggested 26 °C as the optimum temperature for the optional cognitive performance. In another recent study [215], significant differences in participants' addition task performance were found for a "hard" mode but not for "easy" mode between slightly warm (PMV =1) and slightly cooler conditions (PMV = -1). In the study, the participants did not show a significant difference in response time on a choice reaction task for either "hard" or "easy" mode. Also, the participants' response time in two reaction tests ("hard" and "easy" modes) was insignificantly ($p > 0.05$) differentiated at three PMV conditions (-1, 0, and 1). However, the difference in response time was statistically significant ($p < 0.05$) for the Stroop task at the three PMV conditions. Ref [197] stated that the subjects had neutral comfort at both 23°C and 27°C. But the reasoning performance, observed at 27°C, decreased by 11.2% compared to performance at 23°C. The study [195] indicated that only male subjects displayed significant differences in the four-choice test performance as the temperature increased from 28 °C to 33 °C, as well as the text typing test when the temperature increased from 25 °C to 28 °C or 33 °C.

Reasoning and planning skills were found to have a significant relationship with the thermal sensation vote [170]. The study reported that reasoning and planning performance was negatively correlated to TSV^2 and TSV respectively in the warmer temperature cycles starting from 24 °C. Planning skills were more sensitive to heat than reasoning in the rising temperature. That is, a higher rate of temperature increment had detrimental effects on planning, but not on reasoning performance.

Noise

Moderate noise enhances processing difficulties, such as the activation of abstract cognition and enhancing creative performance [257]. It was also found in the same study that mild noise could

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https://doi.org/10.1016/j.buildenv.2021.107647

be a trigger for higher leave creativity, while loud noise reduces the extent of information processing, resulting in cognitive impairment. However, teacher-reported cognition functions of school children showed no significant effects of ambient noise levels upon executive function [258].

Lighting

No significant effect of lighting color temperature (3,000 K vs 4,000 K) was found on the performance of problem solving and judgment [242]. However, another study concluded that "warm" white light (3,000 K) was optimal for problem solving [169]. In addition, high-frequency lighting is perceived as more pleasant than low-frequency lighting and can then enhance problem solving performance [259].

Non-light visual factors

Mehta and Zhu [260] found that red backgrounds enhance motivation, whereas blue improves subjects' creative ability. Blue light enhanced individuals' purchase intentions toward products mainly bought for pleasure or enjoyment, indicating that blue lighting is a contributing factor in participants' altered purchase intentions. In another study, participants' planning skills did not significantly vary when a window view was present or not [214].

4.1.6 Summary of the conventional manual review

Appendix I Tables A2-A6 list the major findings of studies on the association of IEQ factors and cognition. While detailed and informative, the tabulated results of all the reviewed studies might not easily generate a clear "big picture". This is because many studies have reported contradictory or mixed findings. Therefore, we calculated the percentage of studies that revealed statistically significant association (*with the assigned rating "2"*), and the percentage of studies showing mixed association (*with the assigned rating "1"*) between a particular IEQ factor and a cognitive function. For example, 36% of the 16 reviewed studies indicated a mixed association (*rating "1"*) between thermal environment and memory, while only 14% confirmed a statistically significant association (*rating "2"*). Please note that Table 1 does not distinguish between positive and negative associations. Even though the statistics is unable to quantify the effect size of each pair of an IEQ factor and cognitive function, the present approach in Table 1 can still shed lights on the amount of evidence n the topic and the intensity of research inconsistency across various disciplines that may not be easily obtained otherwise.

https://doi.org/10.1016/j.buildenv.2021.107647

Table 1. Percentage of studies reporting different leveles of statistical significance for the associations between IEQ and cognition

	IAQ			Thermal environment			Noise			Lighting			Non-light visual factors			Row average	
	Perc. of sig. ⸸	*Perc. of mixed* ⸸	*# of studies*⸸	*Perc. of sig.*	*Perc. of mixed*	*# of studies*	*Perc. of sig.*	*Perc. of mixed*	*# of studies*	*Perc. of sig.*	*Perc. of mixed*	*# of studies*	*Perc. of sig.*	*Perc. of mixed*	*# of studies*	*Perc. of sig.*	*Perc. of sig. or mixed*
Attention	20%	20%	6	10%	30%	11	25%	25%	5	33%	34%	6	50%	50%	5	***28%***	***31%***
Perception	0	0	1	0	50%	3	NA	NA	0	0	67%	3	NA	NA	0	***25%***	***38%***
Memory	0	25%	8	14%	36%	16	71%	29%	8	29%	28%	7	0	100%	1	***23%***	***43%***
Language function	0	0	2	33%	0%	4	67%	33%	10	50%	0%	2	0	100%	1	***30%***	***26%***
Higher order cognitive skills	50%	33%	8	19%	50%	17	20%	40%	5	33%	0%	6	50%	0%	2	***34%***	***25%***
Column average	***14%***	***15%***		***15%***	***33%***		***57%***	***25%***		***29%***	***32%***		***25%***	***63%***			

⸸ "Perc. of sig.": the percentage of all reviewed studies in Appendix I Tables A2-A6 reporting a significant association only (with the rating "2"); "Perc. of mixed": the percentage of studies revealing a mixed association (with the assigned rating of "1"). The description of different rating levels can be found in Section 3.1. "# of studies": the total number of reviewed studies containing all ratings ("0", "1", "2", and "NA").

Table 1 shows that the most examined IEQ factors in the literature are thermal environment, noise, and IAQ, while the most studied cognitive functions are memory, high order cognitive skills, and attention. The research on how IEQ influences perception is quite rare. Overall, for each pair of IEQ and cognition, a statistically significant association ($p < 0.05$) has been identified by a portion of studies in the literature.

To interpret the results from Table 1, the sample size (number of studies) in each cell and the percentage of significant association are both important, as a 100% statistical association reported in only one study may not carry weight. For pairs of IEQ and cognition with more than 5 studies, the percentage of studies reporting a significant association ($p < 0.05$) is 50% between IAQ and higher order cognitive skills, 67% between noise and language function, and 71% between noise and memory. In contrast, the percentages of studies showing a significant association is quite small (< 20%) between IAQ and memory (almost 0%), thermal environment and attention (10%), thermal environment and memory (14%), and thermal environment and higher order cognitive skills (19%).

Each row in Table 1 represents the influence of various IEQ variables on a specific cognitive function. Considering the aggregated effects of all IEQ factors on each cognitive function by averaging the percentages in a given row, approximately 34% of studies on average imply a significant association between IEQ and higher order cognitive skills, while the percentage drops to 30%, 28% and 23% for language functions, attention, and memory, respectively. However, 43% of studies suggest a mixed association between IEQ and memory, followed by 31% for attention, 26% for language function, and 25% for higher order cognitive skills. The small variations in those percentage values do not entitle differentiation between the most and least vulnerable cognitive functions to IEQ. One explanation for this may relate to the difficulty in isolating cognitive functions, particularly in realistic settings.

For each column of Table 1, the average percentage value over five rows of cognitive functions can help identify the influence of a particular IEQ factor on holistic cognitive functions. Approximately 57% of studies found that noise has a significant impact on cognition. Surprisingly, the percentage of studies reporting statistical significance for both IAQ and thermal environment are lower than 20% in terms of the effects on cognition. Even considering both the significant association and mixed association, the percentage is still less than 50%. The results thus suggest extensive inconsistencies in the relevant literature, especially regarding the effects of IAQ or thermal environment on cognition.

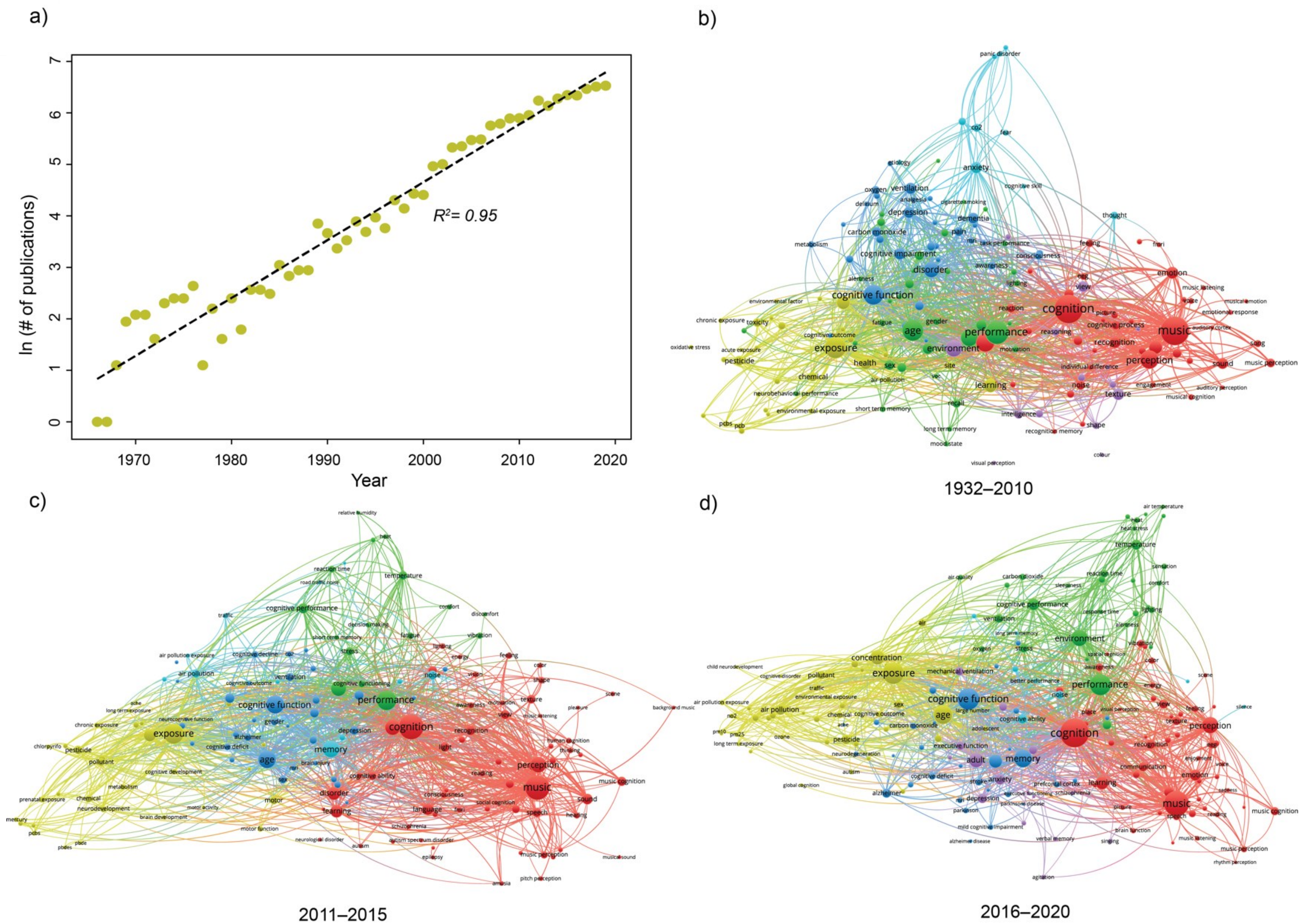
4.2 Keyword co-occurrence patterns identified by text mining

Figure 2 shows the number of publications and knowledge landscapes obtained from keyword co-occurrence analysis at different periods. The connection between two circles refers to co-occurrence instead of statistical association in the same document. A short distance between two keywords represents high co-occurrence. When two keywords are rarely mentioned together in the same document, the two circles containing them are therefore distanced. The number of keywords contained in circles was maximized using a smart local moving algorithm [261]. The size of each circle represents the percentage of the articles mentioning the corresponding keyword in the circle.

The same circle color represents a clustered category using the mapping technique of visualization of similarities (VOS) [262].

The earliest study we found was published in 1932, and since then the number of publications involving both IEQ and cognition have been growing exponentially in the past few decades, as shown in Figure 2a. There were 684 papers published in 2019.

Figure 2b, 2c, and 2d show the relation landscape between IEQ factors and cognitive functions by extracting information from the keywords and abstracts of searched studies, including those reviewed in the manual review, published within the period of 1932 – 2010, 2011– 2015, and 2016 – 2020, respectively. During each period, there were approximately 3000 papers published on average. These results can significantly supplement the detailed manual review described in Appendix I Tables A2-A6 as well as Table 1. The co-occurrence networks in Figure 2b-2d reveal two essential patterns. First, the clustering can be summarized into three major topic themes, cognition (in blue, green, and red), environment (in yellow, aqua, and green), and mediating and confounding factors (in blue and purple) such as *"age", "gender" and "depression."* Second, the landscapes of keywords in Figure 2b-2d depict the evolution of the topics in terms of cognition and IEQ. To better quantify the results displayed in the figure, we summarized common topics sorted on the basis of occurrence frequency during different periods in Table 2 that constitutes a basis for Figure 2b-2d to further reveal the evolvement of the research field . Topics such as *"sound", "recognition", "light", "speech",* and *"noise"* emerged during 2011– 2015, while *"air pollution", "temperature",* and *"mechanical ventilation"* have been paid more attention since 2016. A similar patten has been also observed for cognition, such as new keywords of *"reading", "social cognition", and "language."* In addition to the two patterns, one can observe that music related variables frequently appear along with cognition in the literature during each period.



https://doi.org/10.1016/j.buildenv.2021.107647

***Figure 2**. The number of publications and knowledge landscapes obtained from keyword co-occurrence analysis. a) The temporal number distribution of publications (The figure does not display the only paper published before 1958); b) keyword co-occurrence network with publications between 1932 and 2010 (n = 3421); c) keyword co-occurrence network with publications between 2011 and 2015 (n = 2464); d) keyword co-occurrence network with publications between 2016 and 2020 (n = 2956)*

***Table 2.** Summary of the most frequently mentioned topics during different periods*

Years 1932~2010		Years 2011~2015		Years 2016~2020	
Items	Occurrence	Items	Occurrence	Items	Occurrence
music	662	cognition	683	cognition	950
cognition	585	music	669	music	736
performance	416	exposure	432	cognitive function	547
exposure	384	performance	417	exposure	543
response	325	cognitive function	367	performance	482
cognitive function	314	age	326	age	397
perception	273	memory	310	memory	376
memory	272	response	309	attention	331
attention	239	perception	267	environment	320
environment	220	attention	257	perception	306
disorder	200	environment	257	concentration	236
language	150	disorder	186	disorder	203
concentration	145	concentration	165	learning	203
learning	142	emotion	153	language	184
emotion	115	language	145	cognitive performance	158
recognition	106	**sound**	121	emotion	145
ventilation	106	adult	113	adult	143
anxiety	103	cognitive performance	108	**air pollution**	132
cognitive impairment	103	cognitive impairment	102	anxiety	124
depression	103	**recognition**	100	**temperature**	112
texture	102	**light**	99	**cognitive ability**	110

music cognition	96	music cognition	92	depression	110
dementia	94	anxiety	89	pesticide	101
cognitive performance	93	**speech**	88	communication	100
rhythm	93	**noise**	87	view	99
mood	89	view	86	rhythm	98
sound	88	pesticide	84	mood	97
view	88	mood	83	**recognition**	95
carbon monoxide	77	**texture**	82	Alzheimer	93
pesticide	74	**communication**	79	**mechanical ventilation**	89

Note: The words in bold are emerging items comparing to the previous period.

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https://doi.org/10.1016/j.buildenv.2021.107647

5. Discussion

This review has focused on the association between IEQ factors and the five main categories of cognitive functioning. The reviewed literature consisted of a mixture of laboratory and field work, and both cross-sectional and longitudinal studies. Overall, there is a preponderance of the evidence that almost all IEQ factors, including indoor air quality, thermal environment, noise, lighting, and non-light visual factors could affect cognitive performance to varying degrees. Different IEQ factors can have distinct effects on a specific cognitive function. Likewise, a specific IEQ factor may also exert various impacts, if any, on different cognitive functions. We identify inconsistency, uncertainties, and confounding factors (such as age, sex, and emotion) in the reviewed studies, and point out limitations and future directions.

5.1 Inconsistency, uncertainties, and possible explanations

Appendix I Tables A2-A6 demonstrate inconsistency and uncertainties in reviewed studies. For instance, some experiments indicate that sustained attention is not impaired by aircraft noise [71] or chronic noise exposure [202], while others [263,264] showed that noise does impair both attention and recall. Experimental studies of Ref [9] and Ref [188] reported contradictory results regarding the effects of elevated CO_2 levels on cognitive performance. The research evidence on the effects of lighting on problem-solving is contradictory as well. Ref [169] reported the 'warm' white light source at 300 lx illuminance and the 'cool' white light source at 1,500 lx illuminance to be optimal for subjects' problem solving. However, no significant effect of lighting on problem-solving performance was found by another similar study [242].

We may distill a principled set of sources for the associated variations and inconsistencies that we have observed in the assemblage of data. In general, they relate to complexities in the environmental exposure, variation in the tasks undertaken as representative of both learning and work performance, significant differences between individuals who display that performance, and finally methodological barriers to a full and clear exposition of the relationships evaluated. The factors have been illustrated in Figure 3 for the purpose of ease of discourse. Much of the problem of inconsistency in results arises as a function of the interaction of these identified influences.

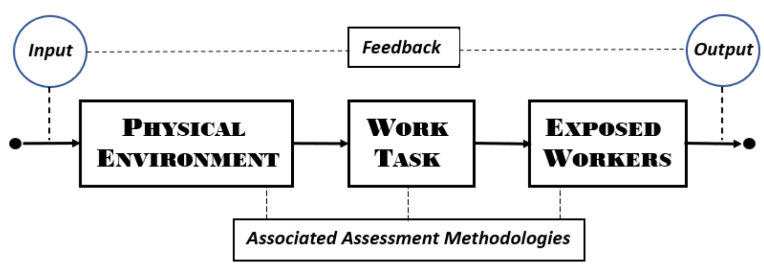

Figure 3. Potential sources of inconsistency and uncertainties related to environments, tasks, and exposed individuals.

From the input conditions composed of the physical environment through the specification of the work tasks involved and the variation of the individuals performing such tasks, we can identify

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https://doi.org/10.1016/j.buildenv.2021.107647

numerous sources of potential inconsistency. Such sources of variability also emanate from the function of feedback loops involved in this process, as well as inherent characteristics and shortfalls in the methods employed to measure response in these varying and disparate sources of influence. The three majorly identified categories are the realms of quite disparate scientific disciplines with their own conventions and traditions. For instance, memory has been assessed by recall tests [223], serial-digit learning tests [184], picture recognition [99], digit span tasks [117,170,265], interviews through telephones [224], electroencephalography (EEG) [266], and functional magnetic resonance imaging (fMRI) [201]. In a review, Zhang and colleagues [234] summarized three common approaches to assess cognitive load/performance. These are primary tasks, subjective perception, and physiological responses [267]. They pointed out that findings from these three approaches do not always agree with each other when applied concurrently. In itself, this can lead to conflicting results in Appendix I Tables A2-A6. Another source of inconsistencies can be exemplified by different ranges of values of the investigated IEQ factors. According to the extended-U model [231,232], people can maintain a stable level of performance over a broad range of environmental stress levels. If the investigated experimental conditions are within this central plateau area, no performance change might be anticipated. It is, therefore, unlikely to find any significant relationship between the environmental factor and cognitive function. However, if the investigated range of environmental stress levels spans beyond this near-optimum range, a significant change of performance may be identified. For example, Ref [265] did not find any significant difference in reasoning skills under two temperature conditions of 22 °C and 25 °C. However, a significant reduction in reasoning was found when the temperature was increased to 30 °C by another similar study [117].

The effects of possible mediators, moderators, confounders, and covariates cannot be ignored as well, such as skill level, emotion, age, gender [268], personal attitude, mood, past events [269], and emotion. Previous studies have revealed that performers' skill levels significantly mediate the influences of environmental stress on cognitive function [16,270,271]. Performers with higher skill levels are less susceptible to performance decrements under environmental stress. In addition, emotion has a mediating effect on cognitive performance [173, 247]. For instance, cognitive performance was negatively affected by heat, partly because people were less motivated when feeling uncomfortable [10]. Age is also a confounding variable. Aging can degrade the sensory and processing functions [271]. Compared to young adults, older adults require a higher-level of illuminance or thermal comfort to maintain the same attention and perception performance [12, 212]. Age influences speech perception in noise conditions [201]. Furthermore, the effects of participants' gender have become manifest in many associated aspects between IEQ and cognitive functions. For example, girls focused much more on a task than boys in experiments with uncomfortable conditions [193,272]. Males showed better performance on an abstract cognitive task [272] and performed significantly better than females in problem solving using an embedded figure task [242]. We discussed in more detail the primary sources of inconsistency (illustrated in Figure 3) in Appendix II.

5.2 Limitations of the present review

We categorized IEQ factors and cognitive functions according to the terminology in the reviewed studies. Some performance tests require multiple cognitive functions and thus are difficult to map into the categories, such as addition, multiplication, and typing. Problem-solving skills involve both attention and memory. Furthermore, the present review does not include the entire spectrum of cognition, partially because there is little research identified regarding social cognition, visuospatial functions, or motor skills when considering the influence of IEQ factors. Also, many studies investigated more than one IEQ and/or cognitive factors, thus could carry more weights in the conclusions of the current analysis. Moreover, some keywords identified in the keyword co-occurrence analysis may not necessarily reflect the exact context of cognition. For instance, *"attention"* is often used in the phrase of "*pay attention to.*" Last, this review does not include studies in languages other than English.

5.3 Recommendation for future research

In addition to the substantial inconsistency in terms of the association between IEQ and cognition, existing literature lacks sufficient and granular evidence to present a comprehensive understanding of the underlying mechanism. First, most studies applied the cross-sectional approach. The consequences of long-term exposure to poor indoor environmental quality thus warrant further research. Second, most existing studies focus on static environments, while dynamic physical environments are rarely explored, especially when alliesthesia [273] is experienced by occupants. Any environmental stimulus that helps to offset the load on the thermo-regulatory system will be pleasantly perceived, and thus can potentially be used to preserve cognitive functions [234]. Future research could use physiopsychological sensors, such as electroencephalogram (EEG), functional magnetic resonance imaging (fMRI) as well as functional near-infrared spectroscopy (fNIRs) to respond to this challenge. Third, the inherent overlap between different cognitive functions, interaction effects of IEQ factors [269], and mediating effects of other factors (e.g., emotion, age, and gender) imply that future research should further decompose each category of IEQ and cognition, by documenting values of all confounding or mediating variables. Otherwise, the true effects could be masked by these diverse influences.

In addition, the contribution of some factors remains missing in the literature, e.g. there is almost no research on how indoor microorganisms such as fungi or molds affect cognition. Research has also revealed that physical activity level could be associated with cognitive capabilities [274]. Would an office worker with a standing or treadmill desk have better cognitive function than his/her sedentary colleagues in the same office? More importantly, even though we may possess a number of dose-response nomograms for the association between IEQ and cognition, we still need to reference underlying theories and associated modeling and simulation to articulate and complete the panoply of empirical results that we do possess, and which have been discussed in this present review.

Albeit any researcher has the flexibility to decide their measurement approach for cognitive performance, it is always worth considering in the experimental design how to compare results with previous studies. Existing studies have been conducted mostly in isolated communities with significantly distinctive measurement protocols to quantify the indoor environment and/or cognition. Hence, the intrinsic complexity of the IEQ-cognition-causality warrants multidisciplinary endeavors in developing a unified framework or protocol to permit the synthesis of "localized" findings. Evidently, such endeavors might involve stakeholders in education research, social behavior, psychology, building science, and medical or health science.

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https://doi.org/10.1016/j.buildenv.2021.107647

6. Summary

This review has examined the effects of indoor environmental quality (IEQ) on cognition that are documented in a broad range of laboratory and field studies. In this work, IEQ in the literature consists of five major categories, i.e., indoor air quality, thermal environment, noise, lighting, and non-light visual factors. The reviewed cognitive functions consist of attention, perception, memory, language function, and higher order cognitive skills. Thermal environment and noise are the most studied IEQ factors, while memory and higher order cognitive skills are the most investigated cognitive functions in the literature based on the manual review.

In general, the reviewed studies demonstrate that poor IEQ is associated with reduced cognitive performance. However, the effects of a specific IEQ factor on different cognitive functions are disparate. Inconsistency and uncertainties have been found, possibly owning to distinct assessment approaches of cognition, different ranges of values of the investigated IEQ factors in the research design, and ignored confounding or mediating variables. Other variables associated with environments, tasks, and occupants could potentially contribute as well.

The keyword co-occurrence analysis of 8,133 studies can work alongside and supplement the conventional manual review to understand the complex network of IEQ and cognitive functions. The findings suggest an exponential growth of studies and emerging topics related to the association between IEQ factors and cognitive functions.

Future studies should improve the temporal granularity of the associations between IEQ and cognition, especially when advanced psychophysiological sensing is available. Also, further research needs to refine the categories of IEQ and cognition, take confounding or mediating factors into consideration, and further promote interdisciplinary collaboration.

Conflicts of interest

The authors declare no competing interests.

Acknowledgment

This work was supported by U.S. National Science Foundation (NSF) under Grant No. 1931077 and Grant No. 2028224. The authors appreciate the valuable comments from reviewers and Dr. Stefano Schiavon of University of California, Berkeley.

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Appendix I

Table A1. *Tasks or methods to assess different cognitive functions*

Cognitive function		Tasks
Attention	General attention*	Stroop task, Serial-digit learning test, d2-test, Corners' Continuous Performance test, Standard Toulouse Pieron questionnaire, Feature match test, Cursor positioning test, Visual search task, Memory-load search task, Curriculum-based measurement, Konzentrations-Leistungs test, Zahlen-Verbindungs test, Necker cube control Test, Symbol digit modalities test, Norwegian version of the reading span test, Double trouble test
	Sustained attention Directed attention	Bourdon test, Toulouse-Pieron test, Psychomotor vigilance test, Chu attention test, Symbol-digit substitution test (SDST), Symbol digit modalities test (SDMT)
Perception	Acoustic perception	Questionnaire related to the environment
	Visual perception	Picture recognition test, Stroop test, Visual search test, Pairing test, Questionnaire related to visual annoyance, Color recognition tasks
Memory	General memory*	Picture recognition
	Short-term memory	Serial-digit learning test, Word recall test, Digit span tests, Code substitution and running memory test
	Long-term memory	Memory typing test, Text recalling test
	Working memory	Subtraction test, Memory span test, 2-Back test, 2-Digit visual addition/subtraction test, Forward digit span test, Computerized test, Visual learning test, Spatial span task, Code substitution, Digit span tests, Operation span task, N-back test, Token search test
	Episodic memory	Telephone interview, The Consortium to Establish a Registry for Alzheimer's Disease-Neuropsychological Assessment Battery, Child memory scale
Language function	Listening comprehension	Questionnaire related to instruction
	Reading comprehension	Proof-reading test, Suffolk reading scale, Oral reading fluency test, SAT comprehension test
	Speech comprehension	Speech test, fMRI test, Identification of words and sentence comprehension, Banford-Kowal-Bench test
Higher order cognitive skills	General higher order cognitive skills*	CNS Vital signs computerized cognitive test, Cognition test CERAD-Plus includes the Mini-Mental State Examination (MMSE), Addition tasks, Attention Deficit Disorder Questionnaire
	Reaction time†	Simple reaction time test, Redirection test, Four choice serial test, Stroop test, Visual signals choice test, Choice reaction time
	Reasoning	Alice Heim 4-I test, Logic problem test, Overlapping test, Grammatical reasoning, Verbal reasoning, Odd-One-Out task, Event sequence and graphic abstracting task

	Decision making	Computer-based test
	Problem solving	Embedded-figure task, She-polish test, Addition task,
	Planning	Spatial planning test, Spatial search task
	Creativity	Creative thinking test, Remote associates test, Idea-generation task

Note: Some instruments, such as the Stroop test, can assess more than one cognitive function.
* *A specific cognition was not explicitly described in the literature.*
† *Reaction time is the time elapsed between the onset of a stimulus and a response to it* [275]. *It consists of simple reaction time, recognition reaction time, and cognitive reaction time. Since it could involve multiple cognitive skills, such as information processing, reasoning, and psychosensory* [276], *we grouped reaction time together with higher order cognitive skills.*

https://doi.org/10.1016/j.buildenv.2021.107647

Table A2. *Summary of IEQ on attention*

Reference	IEQ vs Cognition	Sample size & environmental conditions	Measures of cognitive functions	Major findings	Significance level[⸸]
[119]	IAQ **vs** Attention	18 school children (age between 10 and 11). CO_2 concentration controlled by opening or closing the window to regulate the ventilation; the Mean CO_2 concentration is ranged from 690 ppm to 2909 ppm.	Cognitive Drug Researcher (CDR) computerized cognitive assessment system to measure the subjects' attention level	The increased levels of CO_2 led to a decrement in the power of attention of approximately 5% ($p = 0.004$).	2
[184]	IAQ **vs** Attention	1764 adults (age around 37.5); Estimated exposure levels to PM_{10} and ozone-based on ambient concentrations in the EPA database.	Serial-digit learning test (SDLT) for testing attention. Symbol-digit substitution test (SDST) about coding ability measures an individual's sustained attention.	Increased ozone exposure was correlated with reduced performance in the SDLT test. Each 10-ppb increase in annual ozone was associated with an increased in SDST and SDLT scores by 0.16 and 0.56, which was equal to 3.5 and 5.3 years of aging-related decline in attention function.	N/A
[187]	IAQ **vs** Concentration	417 school students in total in 20 classrooms with mechanical ventilation systems; Median CO_2 concentration of 1045 ppm and 2115 ppm.	d2-test: a paper-and-pencil test with 14 rows of characters to distinguish; The total number of characters processed for handling speed and accuracy; The number of correctly marked target characters minus incorrectly marked distractor characters for concentration assessment.	No significant effect of experimental condition on concentration performance was found. No significant effect of experimental state or median CO_2 level on the "total number of characters processed" could be observed. The concentration performance was decreased by 1.11 points at 2115 ppm of CO_2 in comparison with 1045 ppm. Concentration performance, the total number of characters processed, and total errors changed less than 1.7%.	0
[185]	IAQ **vs** Attention	174 children (46.5% males, age from 7 to 14). Estimate the children's lifetime exposure to black carbon.	Conners' Continuous Performance Test (CPT) for the task-based computerized assessment of attention disorders and neurological functioning.	Exposure to black carbon was associated with increased commission errors and slower hit reaction time (HRT). The associations between BC levels and attention parameters were significantly different ($p < 0.05$) between the middle two BC quartiles and the first BC quartile. But its association with omission errors was not statistically	1

				significant. Boys were more susceptible than girls to potential effects of traffic-related air pollution in some attention domains.	
[188]	IAQ **vs** Attention	25 students (40% males, age around 23). Five conditions mixed with three CO_2 levels (500 ppm, 1000 ppm, and 3000 ppm) and different bio-effluent concentrations.	d2 test: a paper-and-pencil test with 14 rows of characters needed to be distinguished.	No statistically significant effects on perceived air quality and attention performance were found by increasing CO_2 exposure; Exposure to bio-effluent reduced perceived air quality, increased the intensity of reported headache, fatigue, sleepiness, and difficulty in thinking, reduced speed of addition, and decreased the number of correct links made in the cue-utilization test.	0
[189]	IAQ **vs** Attention	31 participants were divided into four groups. CO_2 concentration in the study room was controlled at a normal condition (700 ppm) and a high condition (2700 ppm).	Shifting attention tasks and Stroop test were used for the attention test.	No effect of CO_2 on reaction times, complex attention, simple attention, sustained attention was found.	0
[99]	Thermal environment **vs** Attention	24 participants (50% males, mean age 25 years). Four temperatures, 19°C, 24°C, 27°C, and 32°C were considered in an air-conditioned office with eight fluorescent lamps.	Letter search tests, memory span tests, and picture recognition used in this study were all associated with subjects' attention performance.	No significant effect of temperature on the attention performance was observed in these three tests from both response time and results' accuracy.	0
[117]	Thermal environment **vs** Attention	12 subjects (6 males, average age of 23 years) divided into two groups. One group was exposed to different temperatures in a sequence of 22-30-30-22 °C, while the other group 30-22-22-30 °C.	Computerized test: Stroop - a test of attentional vitality.	The Stroop test performance significantly (p = 0.01) decreased at 30 °C compared with 22 °C when feedback for the test was provided. The performance of the same test was not significantly different (p = 0.09) between the two temperatures without feedback provided.	1
[118]	Thermal environment **vs** attention	56 subjects (28 males, average age of 24.7 years). The temperature changed in order at 26 °C, then 29 °C, then 23 °C. The effect of elevated air movement with an occupant-controlled fan was investigated for 26 °C and 29 °C.	Stroop test was used to measure the ability to switch attention in different tasks.	Using a fan did not significantly affect the performance of a Stroop test at 26 °C (p = 0.12) or 29 °C (p = 0.37).	0

[197]	Thermal environment **vs** Attention	12 subjects (6 males, 18 to 30 years old) divided into two groups. They were exposed to the environment with different temperatures (23 °C and 27 °C).	Computerized test: Stroop - a test of attentional vitality.	The Stroop test performance significantly (*p* = 0.04) decreased at 27 °C compared with 23 °C when there was no feedback. The performance of the same test was not significantly different (*p* = 0.17) between the two temperatures with feedback provided.	1
[194]	Thermal environment **vs** Sustain attention	10 students divided into two groups. They are exposed to six combinations of clothing and air temperature (16 °C, 26 °C, and 36 °C)	The Bourdon test was used to test the subjects' sustained attention.	From the result of the Bourdon test, no significant effects were observed on the change rate of performance from pre-test to post-test. However, the results indicated a higher relative speed (*p* < .05) and a higher relative overall performance (*p* < .05) of sustained attention at 16 °C than 26 °C for the 0.3 clo clothing condition. No significance was found for 0.9 clo regarding the two metrics.	1
[193]	Thermal environment **vs** Attention	117 high school students (aged from 12 to 18 years). One experiment in summer (33.6 °C) and the other in autumn (20.3 °C).	Standard Toulouse Pieron questionnaire to measure the attention index.	The attention index decreased under thermally uncomfortable conditions. The younger the subjects were, the more reduction of the attention index was in thermal discomfort situations.	N/A
[265]	Thermal environment **vs** Concentration	26 office workers (46% males, 73% between 31 and 50 years old, 29% under 30 years old); Temperature conditions: 22 °C and 25°C.	Feature match test to measure concentration.	The test scores for the concentration test were approximately 137 at 25°C and 128 at 22°C. No statistical difference was found.	0
[170]	Thermal environment **vs** Attention and concentration	56 subjects (28 males, mean age of 25 years). The chamber conditions were adjusted by the air volume system from 16°C to 38 °C. The room temperature was cycled at eight different conditions. Illumination was fixed at 500 lx and the background noise was 40 ± 5 dBA.	Attention: feature match test by comparing particular features of various shape images to one another and indicating whether the contents were identical. Concentration: rotations test.	Concentration performance was related to the rate of temperature change. Concentration performance was elevated when the temperature rose faster (Experiment 1 with cooler cycling conditions). Concentration performance had a nearly significant, positive linear relationship with centered air temperature (Experiment 2 with warmer cycling conditions, *p=0.070*).	0
[196]	Thermal environment **vs** Attention	33 students (17 males, aged between 19 and 30 years). The participants needed to finish the designed task in two	Attention performance was measured by Star counting task and vigilance task.	There is no significant improvement in speed (*p* = 0.84) and accuracy (*p* = 0.67) of the Star counting task.	0

		temperature conditions (23 °C and 29 °C).		There is also no significant improvement shown in speed (p = 0.2) and accuracy (p = 0.82) of the vigilance task.	
[195]	Thermal environment **vs** Attention	20 males and 20 females at college-age experienced three operative temperatures: 25.5 °C, 28 °C, and 33 °C.	A cursor positioning test was used to measure attention performance.	No significant difference in positioning performance was found in three temperature conditions for both females and males.	0
[204]	Thermal environment **vs** Attention	33 students (17 males, mean age of 22.1 ± 2.3 years for all participants); Temperatures: 22 and 37 °C; Lighting levels: 200, 500, and 1500 lux with the same color temperature 4500 °C.	Attention level was measured with Conners continuous performance test (CPT), while reaction time (RT) was measured by an RT meter. The attention rate was determined by measuring RT and calculating the number of errors.	For the same lighting condition, an increase in temperature caused an increase in commission error, omission error, response time, and correct response ($p < 0.05$)	2
[202]	Noise **vs** Attention	123 primary school children (54% males; mean age of 9.7 years). The two noise levels: 46.1 Ldn and 62 Ldn (Ldn is a weighted, 24-hour average for community noise exposure).	Visual search task for attention test. Children circled the fish facing the opposite direction for 2 minutes.	No effects of chronic noise exposure on the attention performance test, $t(121) < 1.0$ ($M_{quiet} = 21.60$ and $M_{noisy} = 21.55$ *number of hits; maximum* $= 23$).	0
[12]	Noise **vs** Attention	128 high school students (50% male, 18 to 19 years). The experiment was run in an off-white chamber; Noise: 38 and 58 dBA; Temperature: 21 °C and 27 °C; Illuminance: 300 and 1500 lx.	Memory-load search task: searched random capital letters and recorded the score of accuracy and speed.	The noise accelerated working attention but reduced accuracy (p = 0.035).	2
[71]	Noise **vs** Sustained attention	2844 students (age from 9 to 10 years) from three countries. Aircraft and road traffic noises were recorded in the classroom and outdoors using microphones at the time of testing of cognitive functions.	Sustained attention was measured by adapting the Toulouse Pieron test for classroom use.	Neither aircraft noise nor road traffic noise affected sustained attention.	0
[201]	Noise **vs** Attention	24 adults (12 youngers with the mean age of 21.75, and 12 older with the mean age of 67.5); Signal-	Younger and older subjects identified single words in quiet and two noise conditions (SNR 20	The fMRI results showed reduced activation in the auditory cortex but an increase in attention-related cortical areas (prefrontal and	N/A

		to-noise ratios (SNRs) of stimuli: -5 dB, 20 dB, and quiet condition. The three sets of stimuli were then normalized to 70 dBA.	and -5 dB). The cortical area for attention was measured by fMRI.	precuneus regions) in older subjects, especially in the SNR −5 condition.	
[264]	Noise **vs** Attention	326 children (mean age of 10.4 years) in four groups. Experimental groups were comprised of children exposed to aircraft noise. For the noise group, 65 children were in the old airport (noise changed from 59 to 55 dBA). 111 in the new airport (noise changed from 53 to 55 dBA). Control groups with little exposure to aircraft noise. 43 in the old-airport, no-noise group (noise changed from 68 to 54 dBA); 107 in the new-airport, no noise group (noise changed from 53 to 62 dBA).	Visual search and reaction time were used to test the general attention in this study. Visual search was performed by the embedded-figure tasks. The reaction was executed by pressing the button.	For the visual search task, there were no significant interactions involving chronic aircraft noise over time. For the reaction time, performance in acute noise or no noise condition did not qualify the interaction. The aircraft-noise group at the old airport was slower than its control group (p = 0.026). But at the new airport, the aircraft-noise group was slower than the no-aircraft-noise group (p = 0.039).	1
[206]	Lighting **vs** Concentration	84 students (age from 7 to 8 years). Two lighting conditions: focus lighting (1000 lux, color temperature 6500 K), and normal lighting (500 lux, color temperature 3500 K).	d2 test was used for measuring processing speed, rule compliance, and concentration performance.	No lighting effects were found on either motivation or concentration.	0
[207]	Lighting **vs** Sustained attention	32 participants (16 males, age from 48 to 68 years). BL (Bright light) group (n = 16) and RL (Room light) group (n = 16) worked under standardized conditions over three consecutive simulated night shifts. RL group worked at 300 lux all nights, BL group was exposed to a 4-hour moving light (3000 lux) and 300 lux.	Psychomotor vigilance test (PVT) to test reaction time for sustained attention. Konzentrations-Leistungs-Test (KLT-R) for mental concentration.	Exposure to bright light at night reduced error rates for a concentration performance task. The mean relative frequency of false responses of the concentration performance task was significantly smaller under bright light than under room light ($p < 0.05$). However, the performance (e.g., reaction time) of a sustained attention task was not significantly affected by lighting conditions. ($p = 0.25$).	1

[74]	Lighting **vs** Concentration	58 students (age under 18 years). Two light color temperatures, high (5500 K) vs low (3000 – 3500 K). Two luminance distributions, indirect lighting bounced back from the white ceiling creating large-area lighting source vs purely direct lighting.	d2 test for concentration; German Zahlen-Verbindungs-Test (ZVT) for speed of cognitive processing.	Students showed faster cognitive processing speed and better concentration with blue-enriched white lighting with a high color temperature (5500 K) ($p < 0.001$).	2
[203]	Lighting **vs** Sustained attention	210 undergraduate students (50% males; age from 18 to 23 years). Three correlated color temperatures (CCT): 2700 K, 4300 K, and 6500 K while maintaining the same illuminance of 500 lux.	Chu Attention test for focused and sustained attention.	CCTs affected attention. In specific, the 4300 K condition resulted in significantly better focused and sustained attention (for males, $p = 0.302$. for females, $p = 0.049$).	1
[204]	Lighting **vs** Attention	33 students (17 males, mean age of 22.1 ± 2.3 years). Temperatures: 22 and 37 ℃; lighting levels: 200, 500, and 1500 lux with the same color temperature 4500 ℃.	Attention level was measured with Conners continuous performance test (CPT), while reaction time (RT) was measured by an RT meter (not described in the original paper). The attention rate was determined by measuring RT and calculating the number of errors.	In the 22 ℃ environment, an increase in lighting levels caused a decrease in commission error, omission error, response time, but a decrease of correct response ($p < 0.05$). In the or 37 ℃ environment, an increase in lighting levels caused an increase in commission error, omission error, the response time ($p < 0.05$).	2
[259]	Lighting **vs** Attention	132 subjects aged from 18 to 44 (66 females, 66 males, the mean age is 26). Dimmable, electronic, high-frequency ballasts (32000 Hz), and conventional, magnetic, low-frequency ballasts (50 Hz) Three types of fluorescent tube: 3000K, 4000K, and 5500K.	Memory-loaded search task was used to test the subjects' attention performance.	No effect was found on attention performance by the lighting conditions.	0

[210]	Non-light visual factors **vs** Direct attention	72 undergraduate students (41.6% male, age from 18 to 25). Four groups in different dormitories with views ranging from natural to all buildings.	The capacity to direct attention was measured by the Necker Cube Control (NCPC) Test and Symbol Digit Modalities Test (SDMT) in a complex task. The Digit span test was a standardized clinical measure of attention in this study.	Subjects who had a natural view scored significantly better on the SDMT which was used for directed attention. The nature view group scored significantly higher in the SDMT ($p < 0.05$). In the NCPC test, the difference of attention score in various views was not significant. The Digit span test also did not indicate the significant difference in attention performance in different view conditions.	1
[211]	Non-light visual factors **vs** Attention	34 students (12 males, average age of 24 years). Participants were randomly assigned to one of two conditions: 1) an office setting with four indoor plants, both flowering and foliage, or 2) the same setting without plants.	Attention capacity was assessed three times by using a Norwegian version of the reading span test.	The study confirmed that natural elements can affect cognitive performance in an office work environment. However, the results varied from the repeated reading span test. The performance was similar in the first and second condition ($p = 0.98$). But a moderate difference in the different views happened in the third condition ($p = 0.08$).	1
[208]	Non-light visual factors **vs** Focused attention	24 kindergarten students (12 boys and 12 girls, mean age of 5.37 years). Two conditions: 1) decorated classroom with science posters, maps, the children's own artwork as a visual distraction, and 2) sparse classroom condition with all materials irrelevant to ongoing instruction removed.	Frequency and duration of off-task behaviors of a child for attention.	Classroom visual environment can affect attention and thereby affect learning in kindergarten children. Children's learning gains were higher in the sparse-classroom condition. The overall percentage of instructional time spent off-task was significantly greater when children were in the decorated classroom ($M = 38.58\%$, $SD = 10.49$) than when they were in the sparse classroom ($M = 28.42\%$, $SD = 13.19$) ($p = 0.015$). Also, learning scores were higher in the sparse-classroom condition (M = 55%) than in the decorated-classroom condition (M = 42%) ($p = 0.011$).	2

[209]	Non-light visual factors **vs** Attention	24 students (45.8% male, age from 20 to 38 years). In a simulated study environment, the color of a Corflute panel on a wall in front of the subjects' desk was manipulated with six options (vivid red, vivid blue, vivid yellow, pale red, pale blue, and pale yellow).	The participants were asked to read a passage and then they answered seven multiple-choice questions. These tests were adopted from the SAT Comprehension Test website.	Pale yellow had positive effects on participants' attention on reading tasks and motivated them to study, while vivid yellow impaired participants' attention.	N/A
[214]	Non-light visual factors **vs** Attention	86 participants (43 males, old than 18 years old). The office-like test room had two views which included one without window view and window view shaded by large overhangs and trees in from	The attention performance was tested by the Double Trouble test.	The participants' score of concentration tests were 5% higher in window condition than the windowless condition ($p = 0.03$)	2

ꜜ**Significance level labeled by authors** (0: no statistical association between cognition and tested IEQ ($p > 0.05$); 1: mixed statistical association for varying levels in different performance tests and/or participant groups; 2: the statistical significance of consistently positive or negative statistical association ($p < 0.05$) between cognition and tested IEQ; N/A: not labeled because no reported *p*-value from the study)

Table A3. *Summary of IEQ on perception*

Reference	IEQ vs Cognition	Sample size & environmental conditions	Measures of cognitive functions	Major findings	Significance level[↓]
[119]	IAQ **vs** Visual perception	18 school children. CO_2 concentration controlled by opening or closing the window to regulate the ventilation; Mean CO_2 concentration from 690 ppm to 2909 ppm.	A picture recognition test was used to test the subjects' visual perception.	The increased levels of CO_2 led to a decrement of accuracy ($p = 0.72$) and an increasement of reaction time in the visual perception test ($p = 0.15$).	0
[277]	Thermal environment **vs** Visual perception	32 students (16 males). The test room was controlled with four temperature conditions: 26 °C, 30 °C, 33 °C, and 37 °C and two relative humidity levels.	Stroop test was used to measure visual perception.	The Stroop test result showed the best performance (accuracy and speed) when the temperature was 30 °C. The performance was generally better at 50% than 70% of relative humidity.	N/A
[278]	Thermal environment **vs** Perception	21 participants (6 females, 15 males aged from 18 to 20 years old). They needed to finish tasks in three different indoor air temperatures (17 °C, 21 °C, and 28 °C)	A letter search was used to measure the subjects' visual search. The overlapping test was used to test the subjects' spatial orientation. The carryover effects were corrected for the measured performance.	The visual search performance had the highest correct ratio when the temperature was 17 °C ($p = 0.06$). But the response time was the shortest when the temperature was 21 °C ($p = 0.46$). The overlapping performance had the highest correct ratio ($p = 0.15$) and the shortest response time when the temperature is 21 °C ($p = 0.09$).	0
[215]	Thermal environment **vs** Visual perception	15 students (ages between 22 and 33). In the climate chamber, the temperature was set as slightly cool (21.7 °C), neutral (25.2 °C), and slightly warm (28.6 °C),	A visual search task was used to measure subjects' visual perception ability. It requires the subject to rapidly and accurately search for the target object.	The result table shows the subjects' visual perception were significantly different in the cool and warm condition ($p < 0.05$). But there was not too much difference for the subjects in neutral with the other two conditions.	1
[219]	Lighting **vs** Visual perception	12 observers. Facial recognition with top lighting vs bottom lighting.	The accuracy of matching the view and the objects; Observers were presented with pairs of faces and had to decide if they were of the same or different people, that is, whether the faces were the same or different in shape.	Top-lit three-quarter and full-face was best for male items ($p < 0.05$). But no difference between the top and bottom lighting directions for profile views. There were no significant effects of light or view from any direction for female items.	1

[218]	Lighting **vs** Visual perception	20 students (9 males, mean age of 25). Illuminance level: 500 lx and 750 lx; Light color temperature: 3000 K, 4000 K, and 6500 K.	Questionnaires for visual annoyance including annoyance with tasks, visual satisfaction with a light color, and visual distraction. Computer and paper-based reading tasks to identify letters 'eul' and 'reul' in the paragraphs.	Under 500 lx condition, subjects preferred the color of the 6500 K for better visual perception. Occupants preferred 500 lx under the 6500 K condition, and 500 lx and 750 lx under the 4,000 K condition, reporting better visual satisfaction when performing office tasks.	N/A
[221]	Lighting **vs** Visual perception	24 subjects (20 male and 4 female) mean age is 21.46 years. Four lighting condition was used in the test for different lighting condition. The average color temperature of them are traditional fluorescent lighting (3345 K), and three LED lighting (4175K, 5448K, and 6029K).	Color recognition tasks include the pseudoisochromatic plates and the Farnsworth-Munsell 100 color hue test. Visual acuity task was used for the subjects to read the entire chart.	In Color task 1, the results did not reveal a significant difference in correct response in four light condition (p = 0.89). The time needed to complete the Color task 2 is less as the color temperature increase (p = 0.02). But the error rates of the three conditions did not vary significantly (p = 0.29). For the visual acuity task, the error rates did not reveal a difference as a function of lighting condition (p = 0.38).	1

ⱡ**Significance level labeled by authors** (0: no statistical association between cognition and tested IEQ (p>0.05); 1: mixed statistical association for varying levels in different performance tests and/or participant groups; 2: the statistical significance of consistent positive or negative statistical association (p<0.05) between cognition and tested IEQ; N/A: not labeled because no reported p-value from the study)

https://doi.org/10.1016/j.buildenv.2021.107647

Table A4. Summary of IEQ on memory

Reference	IEQ vs Cognition	Sample size & environmental conditions	Measures of cognitive functions	Major findings	Significance level⸸
[184]	IAQ **vs** Short memory	1764 adults (average age of 37.5 years. Ambient PM_{10} and ozone concentration were retrieved from EPA Aerometric Information Retrieval system database.	A simple reaction time test (SRTT) measuring motor response speed to a visual stimulus; A symbol-digit substitution test (SDST) for coding ability; and a serial-digit learning test (SDLT) for attention and short-term memory.	Increased levels of estimated annual ozone exposure were correlated with reduced performance in the SDLT test. Each 10 ppb increase in annual ozone was associated with increased SDLT scores by 0.56.	N/A
[188]	IAQ **vs** Memory	25 students (40% males, age around 23). Five conditions mixed with three CO_2 levels (500 ppm, 1000 ppm, and 3000 ppm) and different bio-effluent concentrations.	Digit span memory test which needed subjects to recall and reproduce the string by sequence.	No statistically significant effects of CO_2 or bioeffluent concentrations on memory performance using the digit span test.	0
[224]	IAQ **vs** Episodic memory	13996 old adults (44% males, the mean age of 64 years). Cross-sectional association between residential $PM_{2.5}$ concentration and cognitive functions.	Telephone interview for cognitive status. Two separate components of cognitive functions of episodic memory and mental status were measured in the experiment.	Older adults had a worse cognitive function in the area with higher $PM_{2.5}$. The episodic memory performance was decreased as the concentration of $PM_{2.5}$ rose. Part of the results were significant ($p < 0.05$).	1
[255]	IAQ **vs** Short-term memory	10308 old adults (mean age 66 years). The annual average concentration of $PM_{2.5}$ and PM_{10} from 2003 to 2009.	Short-term verbal memory was measured by a 20-word free-recall test in which participants were presented a list of 20 1-or-2 syllable words at 2-second intervals and then were asked to recall them by writing (in any order, within 2 minutes).	All particle metrics were associated with lower scores of memory test performance during the 2007–2009. Higher $PM_{2.5}$ of 1.1 $\mu g/m^3$ was associated with a 0.03 5-year decline in standardized memory score and a 0.04 decline when participants remained in London between study waves. It did not support the hypothesis that traffic-related particles were more strongly associated with cognitive function than particles from all sources.	N/A

[223]	IAQ **vs** Working memory	780 old adults (39% males, age above 55 years). Pollution levels for each respondent were calculated based on air monitoring data from Environmental Protection Agency's Air Quality System (AQS) monitoring sites within a 60-km radius of the respondent's tract centroid.	Cognitive function was assessed with a serial 3's subtraction test to measure working memory and recall of the date, day of the week, and name of the president and vice-president to measure orientation. It is an assessment abbreviated form of the Short Portable Mental Status Questionnaire (SPMSQ).	The subjects living in areas with greater exposure to $PM_{2.5}$ had an error rate of 1.5 times greater than those exposed to lower $PM_{2.5}$ concentration. The increase in $PM_{2.5}$ associated with increased incident rate ratios of errors.	N/A
[189]	IAQ **vs** Working memory	31 participants were divided into four groups. CO_2 concentration in the study room was controlled at a normal condition (700 ppm) and a high condition (2700 ppm).	Working memory test (third-party CNS software was used)	No effects of CO_2 on the working memory tests were reported.	0
[119]	IAQ **vs** Memory	18 school children. CO_2 concentration controlled by opening or closing the window to regulate the ventilation; Mean CO_2 concentration from 690 ppm to 2909 ppm.	The picture recognition task was used to measure the subjects' memory performance.	No significant effects of CO_2 on memory performance in different CO_2 condition (p = 0.15 for reaction, p = 0.72 for accuracy).	0
[254]	IAQ **vs** Semantic memory and episodic memory	789 elderly women (age around 55 years). Assessment of exposure to $PM_{2.5}$ and nitrogen oxides.	A cognition test *The Consortium to Establish a Registry for Alzheimer's Disease* (CERAD)-Plus includes the Mini-Mental State Examination (MMSE).	Air-pollution was cross-sectionally associated with a lower cognitive function. NO_x showed an association with a decline in the CERAD total score.	N/A
[12]	Thermal environment **vs** Long-term recall and short-term recall	128 high school students (50% males, age of 18 to 19 years). The experiment was run in an off-white chamber, furnished as a neutral office. Low-frequency noise: 38 and 58 dBA; Temperature: 21 ℃ and 27 ℃; Illuminance: 300 and 1500 lx.	Long-term recall: read a seven pages text about the ancient culture and answered six knowledge questions and eighteen multiple-choice questions after 130 min. Short-term recall: write down all the words they recalled after three wordlists were presented on a PC-screen.	Interactions were found between noise and heat on the long-term recall of a text, and between noise and light on the free recall of emotionally toned words. Long-term recall: Performance was better in low noise environment 38 dBA than in high noise 58 dBA when the temperature was 27 °C (p = 0.016). Short-term recall: More words were remembered at 21 °C than 27 °C (p = 0.009).	2

[233]	Thermal environment **vs** Recall	18 male university students. Exposed for 1 hour in the chamber at dry bulb/wet bulb temperatures of 26.7/17.2 °C, 43.3/27.8 °C, and 48.9/31.1 °C.	Recall test of wordlists and digit-span tests for short-memory.	The average recall dropped significantly as environmental temperature increased. From the results of mean error rate, the recall decrement from 43.3/27.8 °C (dry/wet bulb) to 48.9/31.1 °C (dry/wet bulb) was statistically significant ($p < 0.05$), but the drop of the recall performance between 26.7/17.2 °C and 43.3/27.8 °C was not significant.	1
[235]	Thermal environment **vs** Long-term memory and short-term memory	20 subjects (50% males, age from 20 to 26 years). Core body temperature was raised to 38.80–39.05 °C within a few minutes by immersion in water at 41 °C.	Long-term memory was assessed by a test that needs the subjects to learn a passage of prose containing 20 facts in 3 min and then recall it 1 h later. Short-term memory was measured by the ability to repeat digit spans forward and backward.	A high core temperature did not affect the ability to learn new facts by the either free or cued recall. It also had no significant effect on short-term memory. However, the increase in core temperature was associated with a significant increase in the speed of the performance of the tests and with a significant decrease in alertness and an increase in irritability.	N/A
[10]	Thermal environment vs Long-term memory	36 students (50% males, the mean age of 23.3 years). Group A (20 subjects) was exposed to five air temperatures (22 °C, 24 °C, 26 °C, 29 °C, 32 °C), while Group B (16 subjects) was only exposed to 26℃.	Memory typing was used as simulated office work. According to the human cognitive process, memory typing belonged to a long-term memory task and needed a relatively high mental demand.	The optimum temperature range for the performance of memory typing in this study was between 22 ℃ and 26 ℃. The performance of memory typing was a little better at 26℃ compared to other conditions. The regression results showed that subjects had the optimum performance when the temperature was 25.8 °C. The performance at 26 °C was significantly higher than that of other temperatures ($p < 0.01$).	2
[99]	Thermal environment **vs** Working memory and learning memory	24 participants (50% males, mean age 25 years). Four temperatures, 19℃, 24℃, 27℃, and 32℃ were considered in an air-conditioned office with eight fluorescent lamps.	Picture recognition as the visual recognition memory and attention task; Memory span test for verbal working memory and attention; Symbol-digit modalities test for learning memory assessment.	No significant effect of temperature on the performance of the memory test which was observed within the short duration of experimental sessions in this study. In particular, there was no ideal temperature that produced the highest scores of all memory tests.	0
[118]	Thermal environment **vs**	56 subjects (28 males, average age of 24.7 years); Temperature changed in order at 26 ℃, then 29 ℃, then 23 ℃. The effect of	2-Back(2B) was used to measure subjects' working memory.	Using a fan did not significantly affect the performance of a memory test at 26 ℃ (p = 0.49) or 29 ℃ (p = 0.23).	0

	Working memory	elevated air movement with an occupant-controlled fan was investigated for 26 °C and 29 °C.			
[265]	Thermal environment **vs** Memory	26 office workers (46% males, 73% between 31 and 50 years old, 29% under 30 years old). Temperature conditions: 22 °C and 25°C.	Digit span test was used for memory performance.	The test scores for the digit span test were approximately 7.2 at 25°C and 7.4 at 22°C. No statistical difference was found ($p = 0.218$).	0
[117]	Thermal environment **vs** Working memory	12 subjects (6 males, average age 23 years) divided into two groups. One group was exposed to different temperatures in a sequence of 22-30-30-22 °C, while the other group 30-22-22-30 °C.	Digit span memory and visual learning memory tests were used to measure the subjects' memory performance.	There is no significant difference in digit span test ($p = 0.44$) or visual learning test ($p = 0.51$) in two temperature conditions.	0
[279]	Thermal environment **vs** Working memory	44 students (mean age was 20.2) were divided into two groups. They had cognitive tests in the AC ($n = 24$) and non-AC ($n = 20$) building before (mean temperature of 20.4 °C), during (mean the highest temperature of 33.4 °C), and after (mean the highest temperature of 28.1 °C) a heatwave.	2-digit visual addition/subtraction (ADD) test was used to measure working memory.	Students without AC showed a significant increase (13.3%, $p < 0.001$) in reaction time of the ADD test, and an insignificant reduction (-6.3%, $p = 0.08$) in throughput of the ADD test during heatwaves compared to the students with AC as the baseline.	1
[215]	Thermal environment **vs** Working memory	15 students (ages between 22 and 33). In the climate chamber, the temperature was set as slightly cool (21.7 °C), neutral (25.2 °C), and slightly warm (28.6 °C),	Forward digit span was adapted to test subjects working memory.	The result shows for the easy mode of digit span test, subjects have no significant difference in the three temperatures condition. But for the hard mode, they had a significant difference in slightly cool and warm condition ($p < 0.05$)	1
[197]	Thermal environment **vs** Working memory	12 subjects (6 males, 18 to 30 years old) divided into two groups. They are exposed to different temperatures 23 °C and 27 °C.	Computerized test: Digit span	The performance of Digit Span was not significantly different ($p = 0.50$) between the two temperatures.	0
[277]	Thermal environment **vs**	32 students (16 males). The test room was controlled with four temperature conditions: 26 °C,	Visual learning test	Visual learning test results indicated the best performance (accuracy and speed) when the temperature was 30 °C. The performance was	N/A

	Working memory	30 °C, 33 °C, and 37 °C and two relative humidity levels.		generally better at 50% than 70% of relative humidity.	
[170]	Thermal environment **vs** Working memory	56 subjects (28 males, mean age of 25 years). The chamber conditions adjusted by the air volume system from 16 °C to 38 °C. The room temperature was cycled at eight different conditions. Illumination was fixed at 500 lx and the background noise was 40 ± 5 dBA.	Memory skill: Digit Span and Spatial Span task.	In Experiment 1 (setpoint of 22 °C), the memory and air temperature were very nearly significant (p=0.066). In Experiment 2 (setpoint of 24 °C), no significant effect found between temperature and memory performance. For the Digit Span test in Experiment 1, performance scores in Condition 2 were significantly higher than they were in Condition 1 (P < 0.05). However, the results were not found for the spatial span test.	1
[195]	Thermal environment **vs** Working memory	20 males and 20 females at college-age experienced three operative temperatures: 25.5 °C, 28 °C, and 33 °C.	Running the memory test.	No significant difference in memory performance was found in three temperature conditions.	0
[278]	Thermal environment **vs** Working memory	21 participants (6 females, 15 males aged from 18 to 20 years old). They needed to finish tasks in three different indoor air temperatures (17 °C, 21 °C, and 28 °C)	Digit span was used to measure the subjects' working memory. The carryover effects were corrected for the measured performance.	The memory span performance declined as the temperature was increased. But the result was not significant (p = 0.79).	0
[196]	Thermal environment **vs** Memory	33 students (17 males, aged between 19 and 30 years). The participants needed to finish the designed tasks in two temperature conditions (23 °C and 29 °C).	The operation span task and N-back task were used for working memory. Long-term memory was evaluated through a task of memorizing facts about a specific new theme.	In the N-back task for working memory, the accuracy of the performance was decreased as the temperature was increased from 23 °C to 29 °C (p = 0.46), while the reaction time was significantly longer (p<0.001) at 29 °C. The accuracy of the long-term memory task was decreased at 29 °C compared to 23 °C (p = 0.28).	1
[12]	Noise **vs** Long-term recall and	128 high school students (50% males, age of 18 to 19 years). The experiment was run in an off-white chamber, furnished as a neutral office.	Long-term recall: read a seven pages text about the ancient culture and answered six knowledge questions and eighteen	Interactions were found between noise and heat on the long-term recall of a text, and between noise and light on the free recall of emotionally toned words.	1

	short-term recall	Low-frequency noise: 38 and 58 dBA; Temperature: 21 ℃ and 27 ℃; Illuminance: 300 and 1500 lx.	multiple-choice questions after 130 min. Short-term recall: write down all the words they recalled after three wordlists were presented on a PC-screen.	Long-term recall: Subjects performed better in the high illuminance 1500 lx than in 300 lx ($p = 0.052$). The performance was better in a low noise environment 38 dBA than in high noise 58 dBA when the temperature was 27 ℃ ($p = 0.016$). But the effect of noise was not significant when the temperature was 21 °C.	
[264]	Noise **vs** Long-term memory and Short-term memory	326 children (mean age of 10.4 years) in four groups. Experimental groups were comprised of children exposed to aircraft noise. For the noise group, 65 children were in the old airport (noise changed from 59 to 55 dBA). 111 in the new airport (noise changed from 53 to 55 dBA). Control groups with little exposure to aircraft noise. 43 in the old-airport, no-noise group (noise changed from 68 to 54 dBA); 107 in the new-airport, no noise group (noise changed from 53 to 62 dBA).	Long-term memory: read the text with noise and then recalled the text after one day in silence. Short-term memory: strings of consonants were presented per second over headphones. Then the children were asked to write down as many consonants as they could remember, in the correct position, starting at the end of the sequence.	After the opening of the new Munich International Airport and the termination of the old airport, long-term memory ($p = 0.015$) and reading were impaired in the noise group at the new airport and were improved in the formerly noise-exposed group at the old airport. Short-term memory was also improved in the latter group after the old airport was closed ($p = 0.092$).	2
[201]	Noise **vs** Working memory	24 adults (12 youngers with the mean age of 21.75, and 12 older with the mean age of 67.5). Signal-to-noise ratios (SNRs) of stimuli: -5 dB, 20 dB, and quiet condition. The three sets of stimuli were then normalized to 70 dBA.	Younger and older subjects identified single words in quiet and two noise conditions (SNR 20 and -5 dB). The working memory was measured by fMRI.	The fMRI results showed reduced activation in the auditory cortex but an increase in working memory-related cortical areas (prefrontal and precuneus regions) in older subjects, especially in the SNR −5 condition.	N/A
[247]	Noise **vs** Long-term recall	1358 children (age from 12 to 14 years). Ten noise experiments in the classrooms for recall and recognition. Single and combined noise sources (e.g., train noise, aircraft noise) were presented for 15 min at 55 or 66 dBA L_{eq}.	Three texts about ancient cultures were used as the source of six open-ended recall questions and twelve multiple-choice questions. The scoring system gave points to each item of information the child remembered.	There was a strong noise effect on recall ($p < 0.01$), and a smaller but significant effect on recognition ($p = 0.011$). Train noise and verbal noise did not affect recognition or recall. Some of the pairwise combinations of aircraft noise with train or road traffic interfered with recall and recognition.	2

[202]	Noise **vs** Intentional, incidental, and recognition memory	123 primary school children (54% males; mean age of 9.7 years); The two noise levels: 46.1 Ldn and 62 Ldn (Ldn is a weighted, 24-hour average for community noise exposure).	Free recall and recognition for the puzzle diagrams assessed incidental memory. Children were asked to recognize the correct diagrams from a set with an equal number of correct and incorrect drawings.	Significant effects of chronic noise exposure on both intentional and incidental memory were reported. Intentional memory was significantly better in the low noise environment ($p < 0.02$). Incidental memory performance was degraded by chronic noise exposure ($p < 0.05$). Recognition memory was also worse for the chronically noise-exposed children ($p < 0.04$).	2
[71]	Noise **vs** Episodic memory, working memory	2844 students (age from 9 to 10 years) from three countries Aircraft and road traffic noises were recorded in the classroom and outdoors at the time of testing cognitive functions using microphones.	Episodic memory (recognition and recall) was assessed by a task adapted from the child's memory scale. This task assessed time delayed cued recall and delayed recognition of two stories presented on a compact disc. The search and memory task was used to assess working memory and prospective memory.	A linear exposure-effect association was found between exposure to aircraft noise and impaired recognition memory in children (p=0.0141). Exposure to road traffic noise was linearly associated with increases in episodic memory (conceptual recall: $p = 0.066$; information recall: $p = 0.0489$).	2
[72]	Noise and reverberation time **vs** Memory	Experiment 1: 28 university students (age from 19 to 35 years) in a sound-attenuated climate chamber; Noise condition: one lecture with a broadband noise with the spoken lecture with an S/N ratio of +5dBA; Control condition: spoken lecture with an S/N ratio of +29dBA without background noise. Experiment 2: 19 adolescents (2 males, age around 17 years). Short reverberation condition, 0.3 s in all octave bands from 125 Hz to 4 kHz; Long reverberation time, 1.84 s at 125 Hz, 1.46 s at 250 Hz, 0.94 s at 500 Hz, 0.77 s at 1 kHz, 0.78 s at 2 kHz and 0.68 s at 4 kHz.	Experiment 1: Hearing tests: participants were asked to repeat two lists of ten sentences in different noise conditions. Experiment 2: Participants listened to the 10 paragraphs and answered 20 questions by typing them on the computer keyboard to score their ability to hear the lecture on a 7-point scale.	The participants' memory performance was worse when the lecture was heard in the noise condition than in the control condition ($p < 0.05$). In the long reverberation time condition, participants' memory performance was worse than that in short reverberation time conditions ($p < 0.001$).	2
[70]	Noise **vs** Speech	23 adolescents (9 males, age of 17 years).	The operation span task was used to assess the participants' working memory capacity. Prose memory	The significant difference in participants' scores on the prose memory task was found between the speech noise condition and	1

	prose memory	Experiment 1: sounds from different airborne aircraft were recorded outside using a stereophonic microphone and then were put together with computer software to create 10 sound sequences of aircraft at 55-60 dBA L_{eq}. Experiment 2: the speech was recorded in an echo-free room and then was played back to the participant at around 55-60 dBA L_{eq}.	was tested by two tasks which were combined by the reading phase and recall phase.	silence condition and between speech noise condition and aircraft noise condition ($p < 0.01$). However, the difference was insignificant between the aircraft noise condition and silence condition ($p = 0.24$). The speech was more detrimental to prose memory than is aircraft noise, and individual differences in working memory capacity contributed more to individual differences in susceptibility to the effects of aircraft noise on prose memory than to the effects of speech.	
[12]	Lighting **vs** Long-term recall and short-term recall	128 high school students (50% males, age of 18 to 19 years). The experiment was run in an off-white chamber, furnished as a neutral office. Low-frequency noise: 38 and 58 dBA; Temperature: 21 ℃ and 27 ℃; Illuminance: 300 and 1500 lx.	Long-term recall: read a seven pages text about the ancient culture and answered six knowledge questions and eighteen multiple-choice questions after 130 min. Short-term recall: write down all the words they recalled after three wordlists were presented on a PC-screen.	Interactions were found between noise and light on the free recall of emotionally toned words. Long-term recall: Subjects performed better in the high illuminance 1500 lx than in 300 lx ($p = 0.052$). Short-term recall: When the noise was 38 dBA, more words were remembered at 1500 lx than 300 lx ($p = 0.032$). However, the effect of illumination was insignificant when noise was 58 dBA.	1
[169]	Lighting **vs** Long-term memory	96 subjects (aged from 18 to 55 years). The first experiment was full factorial with two light color temperatures (3000 K vs 4000 K) and two illuminance levels (300 lx vs 1500 lx), while maintaining a high color rendering index (CRI) 95. The second experiment had the same set as the first one except for a low CRI 55.	Long-term recall and recognition task: seven pages of compressed test about an ancient culture as an encoding-retrieval task. In particular, read the text and answered six general knowledge questions and eighteen multiple-choice questions. Free recall task for memory performance: recall wordlists shown on a PC-screen.	In specific, a light color temperature that induced the least negative mood enhanced the performance in the long-term memory and problem-solving tasks in both genders ($p < 0.05$). Also, the combination of color temperature and illuminance that best preserved the positive mood in one gender enhanced this gender's performance in the problem-solving and free recall tasks.	2

[207]	Lighting **vs** Working memory	32 participants (16 males, age from 48 to 68 years). BL (Bright light) group (n = 16) and RL (Room light) group (n = 16) worked under standardized conditions over three consecutive simulated night shifts. RL group worked at 300 lux all nights, and BL group was exposed to a 4-hour moving light (3000 lux) and 300 lux.	One-digit numbers were presented for 1.5 s on a computer screen successively for 5 minutes per session. Subjects were instructed to conduct a task related to the numbers remembered.	Exposure to bright light at night reduced error rates of a working memory task. The mean number of correct responses was significantly higher under bright light than under room light ($p < 0.01$).	2
[242]	Lighting **vs** Memory	40 subjects (50% males, age from 18 to 55 years). Two color temperatures, 3000 K and 4000 K at color rendering index (CRI) of 95, and illuminance level of 1500 lx.	For long-term recall, the subjects need to read the materials and then accomplish the recall and recognition task. For free recall, the subjects need to recall the words they read from the word list.	No significant effect of lighting on the performance of free recall, the long-term recall was obtained.	0
[221]	Lighting **vs** Working memory	24 subjects (20 male and 4 female, mean age are 21.46 years). Four lighting condition was used in the test for different lighting condition. The average color temperature of them are traditional fluorescent lighting (3345 K), and three LED lighting (4175K, 5448K, and 6029K).	The verbal event planning task was used for challenging subjects' verbal working memory. The spatial map study task was used for challenges subjects' spatial working memory.	For both the verbal working memory and spatial working memory test, the accuracy of both tests did not vary significantly as a function of lighting condition ($p > 0.05$). But reaction time of these two tests became less as the increasing color temperature ($p < 0.01$).	1
[259]	Lighting **vs** Long-term memory and short-term memory	132 subjects aged from 18 to 44 (66 females, 66 males, the mean age is 26). Dimmable, electronic, high-frequency ballasts (32000 Hz), and conventional, magnetic, low-frequency ballasts (50 Hz) Three types of fluorescent tube: 3000K, 4000K, and 5500K.	The subjects were asked to finish the 24 questions for recalling the content in the materials read 130 minutes ago.	No effect was found on long-term memory or short-term memory performance by the lighting conditions.	0

[74]	Lighting **vs** Memory	58 students (age under 18 years). Two light color temperatures, high (5500 K) vs low (3000 – 3500 K); Two luminance distributions, indirect lighting bounced back from the white ceiling creating large-area lighting source vs purely direct lighting.	Visual and verbal memory test was used to test the memory retention.	No effects of blue-enriched white lighting on short-term encoding and retrieval of memories were found ($F (3,53) < 1; F (3,52) < 1$).	0
[214]	Non-light visual factors **vs** Working memory and short memory	86 participants (43 males, old than 18 years old). The office-like test room has two views which include one without window view and window view shaded by large overhangs and trees in from	Token Search test was used to test subjects' working-memory and Digit Span test was for short-term memory)	Working memory for window condition was 6% higher compared to windowless one (p = 0.009). But the short-term memory has no significant difference in the two conditions (p = 0.53).	1

ǂ**Significance level labeled by authors** (0: no statistical association between cognition and tested IEQ ($p>0.05$); 1: mixed statistical association for varying levels in different performance tests and/or participant groups; 2: the statistical significance of consistent positive or negative statistical association ($p<0.05$) between cognition and tested IEQ; N/A: not labeled because of no reported *p*-value from the study

Table A5. *Summary of IEQ on language function*

Reference	IEQ vs Cognition	Sample size & environmental conditions	Measures of cognitive functions	Major findings	Significance level[ↆ]
[188]	IAQ **vs** Reading comprehension	25 students (40% males, age around 23). Five conditions mixed with three CO_2 levels (500 ppm, 1000 ppm, and 3000 ppm) and different bio-effluent concentrations.	Proof-reading test which needed subjects to highlight the errors in the printed text.	There is no statistically significant effects of CO_2 or bioeffluent concentrations on proof-reading performance.	0
[246]	IAQ **vs** Reading	Students in 5th grade participate in the task. Monitoring the CO_2 concentration and ventilation rate in fifth-grade classrooms of 54 elementary schools.	The students are asked to take the tasks of math skills and reading skills.	The association observed using linear regression between ventilation rate and the reading score has no statistical significance ($p = 0.56$).	0
[278]	Thermal environment **vs** Reading comprehension	21 participants (6 females, 15 males aged from 18 to 20 years old) They needed to finish tasks in three different indoor air temperatures (17 °C, 21 °C, and 28 °C)	A verbal comprehension task was used to measure the subjects' reading comprehension. The carryover effects were corrected for the measured performance.	The reading comprehension performance had the highest correct ratio when the temperature was 21 °C ($p = 0.63$). But the response time was the shortest when the temperature was 28 °C ($p = 0.16$).	0
[245]	Thermal environment **vs** Reading comprehension	158 undergraduate students (95 males, age from 17 to 49 years). Normal condition: 22.2 °C, 35 dBA and 500 lx; Discomfort condition: 26.7 °C, 60-65 dBA and 2500 lx.	The subjects read a test passage then took an assessment. The Sentence Verification Task (SVT) was used as the test for comprehension. It can be adapted to any reading assignment or oral presentation.	Students in the reading condition have reported no difference between conditions for the reading modality (p = 0.25).	0
[253]	Thermal environment **vs** Speech recognition	24 students (50% male, age from 19 to 27) The indoor environmental chamber with packaged air-conditioners (four thermal conditions with PMV -1.53, 0.03, 1.53, and 1.83), ventilation fan, humidifiers, dehumidifiers, lighting, and loudspeakers (for	Set the duration of exposure and various background noise. In the two different speech-noise-ratio recognition tests, participants need to take the 25-words speech test. This study recorded the normality of the subjective responses to the questionnaire.	Both speech-noise-ration and thermal comfort can affect speech recognition. But only PMV with SNR of 5 dB affects the speech recognition scores.	N/A

		fan and babbles sounds of 45 and 60 dBA).			
[280]	Thermal environment **vs** Reading comprehension	30 subjects (16 males, aged from 18 to 29) were divided into six groups. The experimental room was set at 22 °C, 26 °C, and 30 °C in two noise conditions (35 dBA and 55dBA)	Proof-reading was used to measure subjects' reading comprehension	The proof-reading performance was decreased as the temperature was raised in the same noise condition ($p < 0.05$).	2
[71]	Noise **vs** Reading comprehension	2844 students (age from 9 to 10 years) from three countries Aircraft and road traffic noises were recorded in the classroom and outdoors at the time of testing of cognitive functions using microphones.	Questions on perceived health, and perceptions of noise and annoyance; Questionnaire for the parents to complete including questions on the perceived health of their child. Reading comprehension with nationally standardized and normed tests—Suffolk reading scale, 10 CITO (Centraal Instituute Toets Ontwikkeling) readability index for elementary and special education, and the ECL-2.	A linear exposure-effect association was found between exposure to aircraft noise and impaired reading comprehension ($p = 0.0097$).	2
[251]	Noise **vs** Listening comprehension and speech perception	94 adult students, children in elementary school, 108 first grade students, 149 third grade students participated in the experiment. For the speech perception, the experiment was conducted in two virtual classrooms with two reverberation time (RT) 0.47 and 1.1s. For the listening comprehension, the task was performed in the	The students need to listen to the instruction and take the test to indicate the misunderstanding of the content.	The background speech affects much more on listening comprehension ($p < 0.001$). The classroom noise influenced speech perception more than that by background speech ($p < 0.001$).	2

		room with classroom noise and with background speech.			
[253]	Noise **vs** Speech recognition	24 students (50% male, age from 19 to 27) The indoor environmental chamber with packaged air-conditioners (four thermal conditions with PMV -1.53, 0.03, 1.53, and 1.83), ventilation fan, humidifiers, dehumidifiers, lighting, and loudspeakers (for fan and babbles sounds of 45 and 60 dBA).	Set the duration of exposure and various background noise. In the two different speech-noise-ratio recognition tests, participants need to take the 25-words speech test. This study recorded the normality of the subjective responses to the questionnaire.	Both speech-noise-ration and thermal comfort can affect speech recognition. Speech recognition performance increased as the SNR increase.	N/A
[280]	Noise **vs** Reading comprehension	30 subjects (16 males, aged from 18 to 29) were divided into six groups. The experiment room was set as 22 °C, 26 °C, and 30 °C in two noise condition (35 dBA and 55dBA)	Proof-reading was used to measure subjects reading comprehension.	For the same temperature condition, the proof-reading speed was increased in the noise condition ($p < 0.05$).	2
[264]	Noise **vs** Speech perception	326 children (mean age of 10.4 years) in four groups. Experimental groups were comprised of children exposed to aircraft noise. For the noise group, 65 children were in the old airport (noise changed from 59 to 55 dBA). 111 in the new airport (noise changed from 53 to 55 dBA). Control groups with little exposure to aircraft noise. 43 in the old-airport, no-noise group (noise changed from 68 to 54 dBA); 107 in the new-airport, no noise group (noise changed from 53 to 62 dBA).	Speech perception: the children heard a story under different noise backgrounds (aircraft noise, road noise, and broadband noise) and used buttons to adjust the sound level of the story when it dropped randomly by 10 dBA. They were instructed to re-adjust the volume to the point where they could understand what was said if they concentrated.	Speech perception was improved between before switch and after the switch, but there was no differential improvement between groups. At the new airport, the onset of aircraft noise seemed to block improvement in auditory discrimination from Wave 1 to Wave 3, as evidenced by the group*wave interaction (p <0.001).	1

[201]	Noise **vs** Speech perception	24 adults (12 youngers with the mean age of 21.75, and 12 older with the mean age of 67.5); Signal-to-noise ratios (SNRs) of stimuli: -5 dB, 20 dB, and quiet condition. The three sets of stimuli were then normalized to 70 dBA.	Younger and older subjects identified single words in quiet and two noise conditions (SNR 20 and -5 dB). The speech perception was measured by fMRI to collect the information on cortical cerebral hemodynamics.	Increased cortical activities in general cognitive regions were positively correlated with behavioral performance in older listeners. ANOVA analysis showed a main effect of noise conditions on the accuracy of spoken word processing ($p < 0.001$).	2
[245]	Noise **vs** Reading comprehension	158 undergraduate students (95 males, age from 17 to 49 years). Normal condition: 22.2 °C, 35 dBA and 500 lx; Discomfort condition: 26.7 °C, 60-65 dBA and 2500 lx.	The subjects read a test passage then took an assessment. The Sentence Verification Task (SVT) was used as the test for comprehension. It can be adapted to any reading assignment or oral presentation.	Students outside the comfort zone reported were more negatively affected by the sound of the room. The sound had a more negative effect on their performance than those in the normal condition ($p = 0.02$).	2
[249]	Noise and Reverberation **vs** Speech perception	487 students (first and second grade, 249 boys, mean age from 7 -8 years). The reverberation time of speech from 0.49 to 1.1 seconds, the ambient noise level from 22 – 29 LAeq in empty classrooms. The speech materials were presented with a signal level of 65 dBA.	Identification of single words and sentence comprehension for speech perception.	The students from school 8 in the control room had better improvement in word identification test ($p < 0.01$). In both school 1 and school 8, students had higher accuracy in the extra room than in the classroom. But the effect of the test room and the interaction did not reach significance ($p = 0.09$). No effect of reverberation time had been found on sentence comprehension.	1
[248]	Noise **vs** Speech Perception	66 children (44 males, age from 8-14 years). Grouped based on the performance on the clinical measure of speech-in-noise (SIN) perception and reading. The experiments were performed in quiet and noise conditions (six-talker babble with the signal-to-noise ratio at 10 dB).	Speech understanding in noise was evaluated with the Hearing in Noise Test (HINT) used the Banford-Kowal-Bench (BKB) phonetically balanced sentences appropriate for children at the first-grade reading level and above. Subjects were divided into two groups: 1) top SIN group, >50th percentile in HINT-Front scores, and 2) bottom SIN group <50th percentile in HINT-Front scores.	Background noise delayed the response significantly ($p < 0.001$). In the quiet condition, two groups have the same neural response timing. In the noise condition, bottom groups exhibited greater neural delays relative to the top groups.	2

[252]	Noise **vs** Reading comprehension	40 students (mean age of 23.7, 62.5 female). The irrelevant speech was recorded and played through headphones at approximately 70-75 dBA. The participants were asked to sit in the silent room with listening to the various speech fragments.	Participants need to read the first 5 short texts and answer the accompanying questions in 90 seconds. Then they need to select one from four words to make the sentence which missing one word coherent in the remaining 15 texts.	The irrelevant speech disrupted the reading comprehension ($p<0.05$). But it did not affect the time need to finish the task.	1
[206]	Lighting **vs** Reading comprehension	84 students (age from 7 to 8 years); Two lighting conditions: focus lighting (1000 lux, color temperature 6500 K), and normal lighting (500 lux, color temperature 3500 K).	ORF was used to measure subjects' reading performance for the focus light set on that.	The focus light setting was an instructional technology that improved the reading performance of the participants ($p < 0.001$).	2
[245]	Lighting **vs** perception and comprehension	158 undergraduate students (95 males, age from 17 to 49 years). Normal condition: 22.2 °C, 35 dBA and 500 lx; Discomfort condition: 26.7 °C, 60-65 dBA and 2500 lx.	The subjects read a test passage then took an assessment. The Sentence Verification Task (SVT) was used as the test for comprehension. It can be adapted to any reading assignment or oral presentation.	The light did not affect the participants' performance on their listening or reading.	0
[209]	Non-light visual factors **vs** Reading comprehension	24 students (45.8% male, age from 20 to 38 years). In a simulated study environment, the color of a Corflute panel on a wall in front of the subjects' desk was manipulated with six options (vivid red, vivid blue, vivid yellow, pale red, pale blue, and pale yellow).	The participants were asked to read a passage and then they answered seven multiple-choice questions. These tests were adopted from the SAT Comprehension Test website.	Reading comprehension scores were significantly higher in the vivid color conditions compared to the pale color conditions ($p = 0.022$). But the main effect of hue was not significant ($p = 0.676$).	1

ⱡ**Significance level labeled by authors** (0: no statistical association between cognition and tested IEQ ($p > 0.05$); 1: mixed statistical association for varying levels in different performance tests and/or participant groups; 2: the statistical significance of consistent positive or negative statistical association ($p < 0.05$) between cognition and tested IEQ; N/A: not labeled because no reported p-value from the study)

Table A6. Summary of IEQ on higher order cognitive skills

Reference	IEQ vs	Sample size & environmental conditions	Measures of cognitive functions	Major findings	Significance level⸸
[214]	IAQ **vs** Reaction time (simple and choice)	18 school children (age between 10 and 11). CO_2 concentration controlled by opening or closing the window to regulate the ventilation; the Mean CO_2 concentration is ranged from 690 ppm to 2909 ppm.	Cognitive Drug Researcher (CDR) computerized cognitive assessment system to measure the subjects' attention level	The increased levels of CO_2 led to a decrement in the accuracy of choice reaction ($p = 0.75$) while with an increment in reaction time ($p = 0.06$). The simple reaction time was increased by the increase of CO_2 concentration ($p = 0.02$).	1
[184]	IAQ **vs** Reaction time	1764 adults (age around 37.5). Estimated exposure levels to PM_{10} and ozone-based on ambient concentrations in the EPA database.	A simple reaction time test (SRTT) to measure visuomotor speed to a visual stimulus.	Increased ozone exposure was not correlated with reduced performance in the SRTT test.	0
[255]	IAQ **vs** Reasoning	10308 old adults (mean age 66 years); The annual average concentration of $PM_{2.5}$ and PM_{10} from 2003 to 2009.	Alice Heim 4-I test to measure reasoning performance.	Low reasoning performance was associated with all particle metrics， especially for the years more distant in time.	N/A
[188]	IAQ **vs** Calculation and redirection test	25 students (40% males, age around 23). Five conditions mixed with three CO_2 levels (500 ppm, 1000 ppm, and 3000 ppm) and different bio-effluent concentrations.	The redirection test was used to record the response time and error rate. The task was to state whether the disk was in the same direction as the person's face in the image. Also, an additional test (arithmetical calculation) was applied to evaluate speed and error rates.	Exposures to bioeffluents with injected CO_2 at 3000 ppm reduced the speed of addition (for speed $p = 0.023$; for error rate $p = 0.049$), and the response time in a redirection task, and significantly affected speed ($p=0.023$) and error rates of the addition test ($p = 0.049$).	2
[189]	IAQ **vs** Executive function and reaction time	31 participants were divided into four groups. CO_2 concentration in the study room was controlled as normal condition (700 ppm) and high condition (2700 ppm).	CNS Vital signs computerized cognitive test battery	For the executive function test, significant effects of condition with scores in the normal CO_2 concentration condition which was better the baseline ($p = 0.01$). But there was no effect on reaction time performance in different IAQ environment.	1

[254]	IAQ **vs** Visuo-construction	789 elderly women (age around 55 years). Assessment of exposure to $PM_{2.5}$ and nitrogen oxides.	Cognition test CERAD-Plus includes the Mini-Mental State Examination (MMSE).	Air-pollution was cross-sectionally associated with lower cognitive function. NO_x showed an association with a decline in the CERAD total score.	N/A
[35]	IAQ **vs** Decision making	22 students (10 males, age from 18-39 years). Median CO_2 concentration approximately 600, 1000, and 2500 ppm.	The computer-based test was used to measure decision-making performance.	Compare to 600 ppm of CO_2, moderate, and statistically significant decrements occurred in six of nine scales of decision-making performance as the increasing CO_2 concentration (p < 0.001). At 2500 ppm, large and statistically significant reductions occurred in seven scales of decision-making performance (raw score ratios, 0.06–0.56), but performance on the focused activity scale increased.	2
[281]	IAQ **vs** Decision making	32 adult subjects were divided into eight study groups. Four groups subjects participated in the chamber with varying VR (ventilation rate) per occupants (8.5 and 2.6 L/s per person). Other four groups participated in the study of varying VR per floor area (5.5 and 0.8 L/s-m^2)	Strategic management simulation (SMS) which is a web-based simulation was used to assess decision-making performance.	Decision-making performance decreased as the VR reduce in both experiments. From the performance metric tables, almost all the factors that contribute to decision-making were different significantly in various ventilation condition (p < 0.05)	2
[194]	Thermal environment **vs** Calculation	10 students divided into two groups. They are exposed to six combinations of clothing and air temperature (16 °C, 26 °C, and 36 °C)	Calculation test which was based on the Uchida-Kraepelin test form was used	There were no significant differences were observed in the 5-minutes mean accuracy and 5-minutes overall performance. These results suggest that pre-test conditions significantly affected post-test conditions concerning speed but exerted no effect on accuracy and overall performance. The speed of the test indicated a significant difference (p < .05) between 26°C/0.3 clo and 36°C/0.3 clo at the fourth minute; however, no significant differences were observed between other clothing or temperature conditions. In particular, the most significant changes were observed at 26°C (e.g., the 1st minute vs the 2nd	1

				minute, $p < .01$, for 0.3 clo). During the first minute, accuracy ($p < .05$) and overall performance ($p < .05$) were higher at 26 °C than 36 °C for 0.9 clo.	
[195]	Thermal environment **vs** Addition and choice reaction test	20 males and 20 females at college age. They experienced three operative temperatures: 25.5 °C, 28 °C, and 33 °C.	Addition task, four-choice serial reaction time, and code substitution	No significant difference in performance was found in all tests between three conditions for females. For males, typing performance was significantly lower at 25 °C than the other two conditions ($p < 0.05$); The performance of the four-choice serial reaction time task was significantly lower at 33 °C than the other two conditions ($p < 0.05$).	1
[118]	Thermal environment **vs** Choice and executive function	56 subjects (28 males, average age of 24.7 years). The temperature changed in order at 26 °C, then 29 °C, then 23 °C. The effect of elevated air movement with an occupant-controlled fan was investigated for 26 °C and 29 °C.	Choice reaction time with three choices to test the processing speed and alertness. Stroop test was used to measure inhibition.	In the same temperature condition, the use of a fan did not significantly affect the subjects' performance of a choice reaction at 26 °C ($p = 0.57$) or 29 °C ($p = 0.34$). Similar, using a fan did not significantly affect the performance of a Stroop test at 26 °C ($p = 0.12$) or 29 °C ($p = 0.37$).	0
[204]	Thermal environment **vs** Reaction time (simple, selective, and diagnostic)	33 students (17 males, mean age of 22.1 ± 2.3 years). Temperatures: 22 and 37 °C; lighting levels: 200, 500, and 1500 lux with the same color temperature 4500 °C.	Reaction time (RT) was measured by an RT meter (Donder's device).	All types of reaction times in higher temperatures (37 °C) have been significantly increased compared to those in lower temperature conditions (22 °C) ($p < 0.05$).	2
[215]	Thermal environment **vs** Calculation and reaction	15 students (ages between 22 and 33). In the climate chamber, the temperature was set as slightly cool (21.7 °C), neutral (25.2 °C), and slightly warm (28.6 °C),	Choice reaction time with three choices to test the processing speed and alertness. A number addition task was used to test subjects' calculation ability.	The results table shows the reaction performance has no significant difference in either easy or hard mode. For the calculation ability, the subjects only had significantly different performances when they were in cool and warm conditions for the hard-mode test ($p < 0.05$).	1

[99]	Thermal environment **vs** Conditional reasoning and Visual choice RT	24 participants (50% males, mean age 25 years). Four temperatures, 19 °C, 24 °C, 27 °C, and 32 °C were considered in an air-conditioned office with eight fluorescent lamps.	Visual choice reaction time to measure response speed and accuracy to visual signals. Stimuli consisting of arrow and triangle were displayed one at a time on the screen. A verbal deductive reasoning task was used for conditional reasoning tests. The spatial image was sued for measuring spatial reasoning.	Participants performed tasks most quickly at 32 °C and lowest at 19 °C. The variation of response time between 24 °C and 27 °C was smallest compared with other temperature pairs, and the response time of 27 °C was longer than that of 24 °C (p = 0.887). The large variance of accuracy and speed indicated that there were large individual differences in the performance of neurobehavioral tests. For reasoning test, there was no significant difference of accuracy (p = 0.25 and p = 0.274) and response time (p = 0.61 and p = 0.607) for subjects in both two tests.	0
[12]	Thermal environment **vs** Problem solving	128 high school students (50% males, age of 18 to 19 years). The experiment was run in an off-white chamber, furnished as a neutral office; Low-frequency noise: 38 and 58 dBA; Temperature: 21 °C and 27 °C; Illuminance: 300 and 1500 lx.	An embedded-figure-task was used to assess problem-solving performance. The participants' task was to find out which one of the five solutions/figures was present in the 16 large targets.	No significant effects were obtained.	0
[235]	Thermal environment **vs** Reasoning	20 subjects (50% males, age from 20 to 26 years). Core body temperature was raised to 38.80–39.05 °C within a few minutes by immersion in water at 41 °C.	Subjects were given 16 simple logic problems. They were asked to decide whether the statement correctly described the sequence of the letters.	No significant difference in the performance of accuracy was found in different control experiments. But the speed of performance was increased as the temperature went up ($p < 0.02$).	1
[279]	Thermal environment **vs** Working memory	44 students (mean age was 20.2) were divided to two groups. They had cognitive tests in the AC (n = 24) and non-AC (n = 20) building before (mean temperature of 20.4 °C), during (mean the highest temperature of 33.4 °C), and after (mean the highest temperature of 28.1 °C) a heatwave.	The Stroop test was used for measuring subjects' inhibition performance.	Students in the non-AC buildings had an increase in reaction time (13.4%, p < 0.0001) and a significant reduction in throughput (9.9%, $p < 0.0001$) of Stroop test compared to the subjects in the AC buildings during heatwaves compared to the students with AC as the baseline.	2

[277]	Thermal environment **vs** Reasoning, addition, multiplication, and redirection	32 students (16 males) The test room was controlled with four temperature conditions: 26 °C, 30 °C, 33 °C, and 37 °C and two relative humidity levels.	The overlapping test was used to measure spatial reasoning ability. Redirection was assessed by the spatial orientation test. Addition and multiplication tests were used to examine mental arithmetic ability.	The accuracy of the overlapping test was the highest when the temperature was 33 °C. But the speed was the lowest at the temperature. Accuracies and speeds of the addition and multiplication test were the highest and lowest respectively when the temperature was 30 °C. The speed performance of these four tests was generally better at 50% than 70% of relative humidity. But the difference in accuracy at the two humidity levels was minimized. No statistical significance was provided.	N/A
[117]	Thermal environment **vs** Reasoning, calculation, and text typing	12 subjects (6 males, average age of 23 years) divided into two groups. One group was exposed to different temperatures in a sequence of 22-30-30-22 °C, while the other group 30-22-22-30 °C.	Grammatical reasoning, number calculation, typing test were the test for measuring subjects' higher order cognitive skills.	The performance of reasoning (tasks on grammatical reasoning, calculation, and addition) almost significantly decreased at 30 °C compared with 22 °C. The grammatical reasoning performance reduced by 25% (p = 0.06) at 30 °C. Calculation speed decreased significantly as the temperature increased (p = 0.08). The subjects input more characters at 30 °C for the typing task (p = 0.75), but they also made more errors.	1
[197]	Thermal environment **vs** Reasoning, number calculation, and typing performance	12 subjects (6 males, 18 to 30 years old) divided into two groups. They are exposed to different temperatures 23 °C and 27 °C.	Computerized tests of grammatical reasoning, number calculation, and typing performance.	The typing performance significantly (p < 0.001) decreased at 27 °C compared with 22 °C when there was no feedback. The performance of the same test was not significantly different (p = 0.68) between the two temperatures with feedback provided. Performance in other tests was not significantly different.	1
[265]	Thermal environment **vs** Reasoning and planning	26 office workers (46% males, 73% between 31 and 50 years old, 29% under 30 years old). Temperature conditions: 22 °C and 25 °C.	Reasoning skill was used to measure the subjects' verbal reasoning ability. The planning skill was used to test spatial planning performance.	CBS test scores of the reasoning skill (p = 0.594) and planning skill (p = 0.114) were not significantly affected by temperature.	0

			The two tests were conducted on the platform of CBS.		
[170]	Thermal environment **vs** Reasoning and planning	56 subjects (28 males, mean age of 25 years). The chamber conditions adjusted by the air volume system from 16 ℃ to 38 ℃. The room temperature was cycled at eight different conditions. Illumination was fixed at 500 lx and the background noise was 40 ± 5 dBA.	Reasoning skill: Odd-One-Out task; Grammatical reasoning task. Planning skill: spatial search; Hampshire tree task adopted from the Tower of London test.	No significant correlation was found between reasoning & planning performance and thermal comfort at a lower cooling setpoint of 22 °C. At a higher cooling setpoint of 24 °C, subjects' reasoning and planning performance showed a trend of decline at the higher heat intensity and longer heat exposure. Subjects' reasoning performance score was negatively associated with TSV^2 (TSV: thermal sensation vote), which predicted an optimal reasoning performance around a neutral thermal sensation. Planning performance had a highly significant negative linear relationship with TSV and air temperature (p<0.001).	1
[280]	Thermal environment **vs** Creative thinking	30 subjects (16 males, aged from 18 to 29) were divided into six groups. The experiment room was set as 22 °C, 26 °C, and 30 °C in two noise condition (35 dBA and 55dBA)	Writing words associated to the specific category was used to measure the subjects' creative thinking ability.	For creative thinking, its score of performance was insignificantly decreased as the temperature was increased in 55 dBA conditions, while the performance varied with temperature non-linearly at the 35dBA condition.	0
[278]	Thermal environment **vs** Reasoning, calculation, visual choice	21 participants (6 females, 15 males aged from 18 to 20 years old). They need to finish tasks in three different indoor air temperatures (17 °C, 21 °C, and 28 °C)	Event sequence, spatial image, and graphic abstracting were used to test the participants' reasoning skills. Number calculation was used for calculation ability. The visual choice test was another test for subjects' reaction time.	The correct ratio of all the three tests for reasoning skill was varied at different temperature (event sequence p = 0.25, spatial image p = 0.62, graphic abstracting p = 0.27). The response time was also a function of temperature (event sequence p = 0.61, spatial image p = 0.33, graphic abstracting p = 0.02). For the calculation test, the subjects had the highest correct ratio (p = 0.95) and the	1

			The carryover effects were corrected for the measured performance.	shortest response time when the temperature was 17 °C ($p = 0.19$). The visual choice performance had the highest correct ratio when the temperature was 17 °C ($p = 0.0005$). But the response time was the shortest when the temperature was 21 °C ($p = 0.17$) as the temperature was increased.	
[10]	Thermal environment **vs** Motivation	36 students (50% males, the mean age of 23.3 years). Group A (20 subjects) was exposed to five air temperatures (22 °C, 24 °C, 26 °C, 29 °C, 32 °C), while Group B (16 subjects) was only exposed to 26 °C.	Self-reported motivation on a 7-point scale.	A warm discomfort environment harmed motivation. Warm discomfort environments were more harmful to motivation than cold discomfort environments. The improvement in thermal comfort level also made people more motivated ($p < 0.047$).	2
[12]	Noise **vs** Problem solving	128 high school students (50% males, age of 18 to 19 years). The experiment was run in an off-white chamber, furnished as a neutral office; Low-frequency noise: 38 and 58 dBA; Temperature: 21 °C and 27 °C; Illuminance: 300 and 1500 lx.	An embedded-figure-task was used to assess problem-solving performance. The participants' task was to find out which one of the five solutions/figures was present in the 16 large targets.	No significant effects were obtained.	0
[257]	Noise **vs** Creativity	65 undergraduate students (21 males) for Experiment 1 and 2; 95 students (35 males) for Experiment 3 and 4; 68 students (24 males) for Experiment 5. The high, moderate, and low-noise conditions: the noise level at 85 dB, 70 dB, and 50 dB, respectively. And one control condition that average ambient noise level for each session setting varied between 39 dB and 44 dB, with an overall average of 42 dB	The Remote Associates Test was used to assess creative performance. It was widely used to assess creative thinking in both psychology and marketing research. Idea-generation task: participants were asked to imagine themselves as a mattress manufacturer looking for creative ideas for a new kind of a mattress. Shoe-polish problem-solving task: subjects were asked to generate as	A moderate (70 dB) versus low (50 dB) level of ambient noise enhanced performance on creative tasks. Respondents in the moderate-noise condition generated more correct answers than those in the low-noise, high noise, or control condition ($p < 0.05$). But the time spent in the test of high-noise condition (85 dB) was significantly less than that need in the other condition ($p < 0.05$).	1

			many solutions as they could think of for the given problem.		
[258]	Noise **vs** Executive function	311 children (146 boys, age of 7-11 years). Noise levels in front of children's schools were measured in three daytime intervals (9 to 11 a.m. 12 to 2 pm. 3 to 5 pm). 24-h noise exposure at children's residence was 71 dB on average. Day-time noise level at school: 76 dB and 75 dB for boys and girls respectively.	Teachers rated children's cognitive functions on a five-item scale adapted from the Attention Deficit Disorder Questionnaire.	No significant relation was found between noise levels at school or home and executive function on the overall sample. Traffic noise at home was significantly associated with executive functions (EF) in boys. Ambient noise from street traffic in a major urban center is related to deficits in EF for boys (p = 0.006) but not for girls when they are at home.	1
[222]	Noise **vs** Perceived control	1015 residents (48.5% male). Aircraft noise was measured at numerous residential sites near flight paths in the vicinity of Sydney Airport.	A structured interview assessed aspects of physical and mental health, reactions to noise, attitudes to the noise source, sensitivity to noise, demographic variables, and noise-induced disturbance. Perceived control: each subject was asked "how much control do you personally have over the amount of aircraft noise you hear" based on a 7-point scale self-report (from no control to complete control).	Perceived control had a significant change from high compared to low noise areas ($p <$ 0.05). Perceived control over aircraft noise correlated negatively with some effects of noise (e.g., disturbances of reading and sleep) but not others (e.g., depression and anxiety). Furthermore, these effects were better predicted by perceived control than by noise level.	2
[280]	Noise **vs** Creative thinking	30 subjects (16 males, aged from 18 to 29) were divided into six groups. The experiment room was set as 22 °C, 26 °C, and 30 °C in two noise condition (35 dBA and 55dBA)	Creative thinking was set as the executive function to measure the subjects' performance.	At a certain temperature, creative thinking performance was decreased or increased with the noise level, but not significantly.	0
[12]	Lighting **vs** Problem-solving	128 high school students (50% males, age of 18 to 19 years). The experiment was run in an off-white chamber, furnished as a neutral office; Low-frequency noise: 38 and 58 dBA;	An embedded-figure-task was used to assess problem-solving performance. The participants' task was to find out which one of the five solutions/figures was present in the 16 large targets.	No significant effects were obtained.	0

		Temperature: 21 ℃ and 27 ℃; Illuminance: 300 and 1500 lx.			
[169]	Lighting **vs** Problem-solving	96 subjects (aged from 18 to 55 years). The first experiment was full-factorial with two light color temperatures (3000 K vs 4000 K) and two illuminance levels (300 lx vs 1500 lx) while maintaining a high color rendering index (CRI) 95. The second experiment had the same set as the first one except for a low CRI 55.	The embedded-figure-task used to measure problem-solving performance.	The 'warm' white light source at 300 lx illuminance and the 'cool' white light source at 1500 lx illuminance was optimal for subjects' problem-solving. Females had significantly better problem-solving performance in the warm than in the cool white light source ($p < 0.05$), while males had the opposite performance.	2
[242]	Lighting **vs** Problem-solving motivation and judgment	40 subjects (50% males, age from 18 to 55 years). Two color temperatures, 3000 K and 4000 K at color rendering index (CRI) of 95, and illuminance level of 1500 lx.	The embedded-figure-task was used to measure problem-solving performance. Judgment performance was assessed on a 7-point scale based on a performance appraisal task that consisted neutral (balanced) information about a fictitious employee	No significant effect of lighting on the performance of cognitive tasks was found. Males performed significantly better than females. The results consolidated that males had better performance in an abstract cognitive task. The female rates were rated as significantly more motivated than the male.	0
[195]	Lighting **vs** Number addition	16 college-age males participated in two lighting conditions. 800 lx and 3 lx (temperature fixed at 23.6 °C and RH 37%).	Addition tasks were adopted.	No significant difference in performance was found between two lighting conditions.	0
[204]	Lighting **vs** Reaction time (simple, selective, and diagnostic)	33 students (17 males, mean age of 22.1 ± 2.3 years). Temperatures: 22 and 37 ℃; lighting levels: 200, 500, and 1500 lux with the same color temperature 4500 ℃.	Reaction time (RT) was measured by an RT meter (Donder's device).	The lighting level on all types of reaction time was statistically significant ($p < 0.001$).	2

[259]	Lighting **vs** Problem solving	132 subjects aged from 18 to 44 (66 females, 66 males, the mean age is 26). Dimmable, electronic, high-frequency ballasts (32000 Hz), and conventional, magnetic, low-frequency ballasts (50 Hz) Three types of fluorescent tube: 3000K, 4000K, and 5500K.	The embedded figure task	A significant improvement in problem solving performance when the lighting is high frequency ($p = 0.06$).	0
[260]	Non-light visual factors **vs** Creativity	208 and 118 participants for two studies on creativity. The color was manipulated through the background screen color. Hue (e.g., red versus blue) was adjusted, and chroma and value were kept constant.	A creative task where subjects were asked to generate as many creative uses for a brick as they could think of within 1 min. The Remote Associate's Test (RAT) was used to test creative thinking.	Red color enhanced performance on a detail-oriented task, whereas blue color enhanced performance on a creative task ($p < 0.03$).	2
[214]	Non-light visual factors **vs** Planning	86 participants (43 males, old than 18 years old). The office-like test room has two views which include one without window view and window view shaded by large overhangs and trees in from	Spatial planning was selected for measuring the participants' planning performance.	The planning test results did not show a significant difference between the two window conditions ($p = 0.53$).	0

ᵻ**Significance level labeled by authors** (0: no statistical association between cognition and tested IEQ ($p > 0.05$); 1: mixed statistical association for varying levels in different performance tests and/or participant groups; 2: the statistical significance of consistent positive or negative statistical association ($p < 0.05$) between cognition and tested IEQ; N/A: not labeled because no reported p-value from the study)

Appendix II

Sources of Potential Inconsistency

The first source of impact on associations between IEQ and cognition emanates from assessment of the physical environment itself. While much basic knowledge can be derived from the more pristine investigations of single factors (e.g., the effect of thermal state on sustained attention [282], actual working conditions are always interactive in their constitution. Thus, temperature level is a ubiquitous presence, as is sound presence, air quality variation etc. The problem here is that the number of potential interactive states of the environment itself rapidly proliferate, and this effect occurs even independent of the essential dynamics of changing states over time. In some ways, inconsistency also emerges here from the disparate base disciplines that underlie measure in many of these areas. Some sources of influence (e.g., temperature, sound), rely on a foundation in physics, others (e.g., air pollutants) can be underwritten by studies of chemistry of particulate studies. More complex sources of influence, such as air exchange, as founded upon an extensive body of practical investigation that has traditionally drawn on an amalgam of disciplinary insights. What this means is that differing cadres of scientific investigators and their associated professional bodies, tend to adopt and prefer their own measurement techniques, developed assessment scales, and then associated applicable standards. None of these are either 'right' or 'wrong' per se, rather the inter-disciplinary cross-talk tends to inject degrees of uncertainty and confusion, most especially when linguistic terms common to each, are employed in diverse ways (and see [283]).

It is across such disciplinary and divisional boundaries that we have to face the behemoth of interaction proliferation [284]. It is by no means solely in the area of IEQ that proliferating interactions plague those who seek deterministic specification, especially using formal methods. The problem derives from the fact that as we add more and more factors, involved in the consideration of practical indoor environments, so the number of possible states increases almost exponentially. And, as we shall see, the effects of many of these factors on cognition is not a linear one, but rather exhibit non-linear effects with the degree of stress each particular factor exerts.

Were these effects all, we might be quite sanguine about some eventual resolution of the interaction problem, most especially because IEQ concerns are actually bounded within fairly narrow limits of the possible ranges of factors involved (e.g., we would not normally evaluate noise effects above 100 dB(A), since this would imply an unacceptable facility design in the first place). Yet now we have to consider problems and issue that emerge when we begin to consider the task, or range of tasks, that the exposed individual is performing in their workplace. As we have seen, these differing forms of task can themselves present very wide-ranging and disparate forms of cognitive demand. Where one profession features an emphasis on memory, another can be characterized by time-pressure decision-making, etc. Our knowledge of the discrete effects of individual sources of disturbance on specific facets of cognition (e.g., attention) has been improving across the decades. However, precisely how each of these elements of cognition then match to specific professional activities is much less well understood. The area of cognitive task analysis has wrestled with this difficult issue and has made some degree of progress. However, one particular hurdle in terms of clearer understanding, derives from the fact that many modern work situations either encourage or mandate that individual's multi-task in order to resolve the demands set before them. This creates

THE MANUSCRIPT HAS BEEN PUBLISHED ON BUILDING AND ENVIRONMENT (2021)
https://doi.org/10.1016/j.buildenv.2021.107647

the issue of stability in which, at one moment, a required task may feature important aspects of perception, while at the next, it emphasizes critical elements of decision-making. We can witness this in safety-critical professions such as air-traffic control in which it is vital that the controller sustain their situation awareness, yet at the same time they have to switch to decision-making in determining the advised path of an aircraft on their screen. These sequences of fluctuating cognitive demand profiles can be repeated many times per minute. These represent largely acute challenges, but human beings learn over time and become better, yet they are also fatigued across a work shift and so experienced degraded performance. Each of these acute and chronic sources of instability add to those already noted for establishing the precise nature of the IEQ experienced. They also lead us to the next source of inconsistency, namely the issue of individual differences.

There are few things that we can assert with certainty about human beings, but one of these is that they each vary across different dimensions. So, while we witness many remaining questions about the physical environment experienced, and the work task that is being performed, we also have an intrinsic source of variation embedded in the fact that there is wide variation amongst workers themselves. Evidently, some people have extensive experience at work, others are new hires. Often such experience co-varies with age, but not necessarily so. Men and women differ in their response to identified factors, and the workplace is now one where multiple gender identifications are becoming more prevalent. One most powerful influence in mediating someone's reaction to their workplace is the degree of autonomy that they can exert. If work occurs in an immalleable place of confinement, as many are now experiencing in 'lockdown' conditions [283], then stress levels build and a general exhaustion syndrome can set in, regardless of the best intentions of workplace designers. If, however, some degree of freedom is given the individual, in terms of controlling their time or the configuration of the space around them, then at least some degree of that general stress is dissipated. In short, people bring a lifetime of experience into their job location and those influences interact with the task they are performing and some intimately affect the outcome of what they are required to do.

This triad of categories represent only those central features which make it problematic to find stable and deterministic patterns to describe the effect of IEQ on cognition. However, there are two other sources that we cannot pass over without some direct comment. As shown in Figure 3, these are connoted by the diversity of applicable measurement techniques, as well as the critical influence of feedback upon all of the noted effects. We deal with them in this order. It will have been noted that as our survey progresses from descriptions of the environment to descriptions of the task, to descriptions of the people involved, the measurement instrument co-vary accordingly. Physical values can be established by external and objective instruments such as those that assess sound pressure level, light level, dry bulb temperature, and the like. However, understanding work tasks means that we must be much more oriented toward cognitive assessment. Here, use of sophisticated techniques to assess brain state, such as EEG, fNIRS etc., are required since the complexity of the entity to be studied has now itself inflated by many orders of magnitude. True, these forms of assessment provide 'objective' evidence, but such evidence has to be interpreted in terms of performance accomplished. At the level of the individual worker, we see featured many more psychological forms of test and evaluation. These impose interrogatories upon the consciousness of the individual. And already we have to accept that what a person says is not necessarily related either to their momentary brain state, nor the instantaneous state of the indoor environment (and see [267]). In brief, these differing instruments tend to access different orders of information, and almost as critically, at differing temporal levels. Thus, while EEG has a time-base commonly measured in milliseconds, a psychological survey instrument might ask about feelings concerning a whole work shift or more. At the same time, those instruments recording IEQ might integrate over minutes, hours, or even days. These disparate time-bases ought to warn us that strong consistency should not be expected, even if the underlying relationship are coherent and discoverable. Precisely how we measure and when we measure tends to inject much variance into our possible understanding of underlying effects.

Finally, feedback impacts all of the factors that have been identified as under-writing the current confused state of experimental information relating IEQ to cognition. This is because awareness of circumstances acts immediately to change those circumstances. So, for example, someone rewarded for their past performance may rate current conditions as more productive and comfortable as a result of that approbation and not any manifest change in the environment. The brain too adjusts to reward and punishment, most especially with respect to its own internally generated feedback loops. As a result, trying to establish the specific effects of IEQ on cognition is like a grandiose signal to noise effort in which the experimentalist must seek to elevate the signal to trans-threshold levels while suppressing and trying to eliminate sources of obstructing noise. But all this is occurring in a flux of related and unrelated variation against which the embattled investigator must seek to fight. While we have pointed to a number of the major reasons why the picture lining IEQ to cognition remains an obscured one, these are by no means the only sources of variation which impinge on the process. As noted earlier, social cognitive influences can certainly play a role as can cultural, political, and informational impacts. In short, we have strong reason to believe that IEQ does exert significant impacts on cognition, but we have equally strong reasons to believe that providing a closed-end specification of such influences is liable to prove a difficult and arduous endeavor, and one that will take a significant interval of time to resolve.

THE MANUSCRIPT HAS BEEN PUBLISHED ON BUILDING AND ENVIRONMENT (2021)
https://doi.org/10.1016/j.buildenv.2021.107647