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How Indoor Environmental Quality Affects Occupants' Cognitive Functions: a Critical Review

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Appendix I

1 Indoor Environmental Quality

1.1 Indoor air quality

Indoor air quality (IAQ) is a critical factor that affects both the health and productivity of space's occupants [1]. Indoor air pollutants include carbon dioxide (CO_2) [2], sulfur dioxide (SO_2) [3], nitric oxide (NO) [4], nitrogen dioxide (NO_2) [5], volatile organic compounds (VOCs) [6], semi-volatile organic compounds (SVOCs) [7], levels of particulate matter (PM) [8], biological contaminants [9,10] among many others. Practically, ventilation and indoor CO_2 concentration are used as an indicator or proxy for diverse levels of indoor air quality [11–13]. 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 [14]. Each of these pollutants can influence both acts of cognition as well as rates of learning.

1.2 Thermal environment

The thermal environment is the physical environment that can affect heat transfer in the indoor. It influences the thermal perception of the individual and though that, the thermal comfort of occupants. Thermal comfort is the subjective evaluation of a thermal environment [15] 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) [16]. These go together with other factors such as gender [17], age [18,19], culture [20], exposure time [21], and physiological adaption [22]. 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 [23], an adaptive thermal comfort model [21,24], and the recent personal thermal comfort [25–28] 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 [29].

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 [30], indoor operating equipment [31], and air distribution systems [32], while outdoor noise transmitted into indoor spaces can emanate from road traffic [33,34], aircraft [34,35], outdoor construction [36] and outdoor components of the heating, ventilation, and air conditioning (HVAC) [37]. Noise from traffic, aircraft, public, or equipment generates a complex sound assemblage that can negatively impact memory [38–40]. Even speech from other classrooms in school can influence students' memory in adjacent classes [41]. Occupants' perceptions are affected by both energy intensity and distribution of acoustical stimuli [42].

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 [43]. Light quality for visual comfort is primarily characterized by photometric variables [44–46], glare [47–49], and light color temperature [50,51]. 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 [52]. 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 [53] and supports for stable circadian rhythms [54]. It also helps occupants to generate an active sense of pleasantness and brightness, which is positive for occupants' comfort and productivity [55,56].

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) [57]. 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 [58–60].

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 [61]. Also, indoor visual interests and opportunities for discovery provide intellectual and cognitive stimulation, which have been found to foster creative behaviors [62]. 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 [63]. Natural environments have, as we have noted a restorative effect on attention, according to the attention restoration theory (ART) [64]. A view of natural elements is beneficial for high workability and job satisfaction [65]. 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 [66], while landscapes with greater tree coverage ratios show a higher percentage of proficiency or advancement in reading and mathematics [67].

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 [68]; while [69] 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 [70]. 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 [71]. Other essential cognitions (e.g., social cognition) are also listed (in the unbolded text) but not studied in this current review.

2.1 Attention

Attention is an individual's ability to concentrate on a particular facet of information [72]. Attentional processes can be further categorized as sustained attention [73–75], selective attention [76–79], and divided attention [36,80,81]. Attentional performance can be assessed using the Continuous Performance Task (CPT) [82], reaction time [83], Stroop tasks [84], the attention network test [85], and the dot-probe task [108] among others. For instance, reaction time is the assessment of motor and mental response speeds, as well as measures of movement time [87,88]. It is an important performance measure of multiple cognitive functions beyond attention [89], such as sensory memory [90].

Attention has a limited capacity, people cannot easily focus on more than one stimulus at a time, unless experience with the task has enabled automatic processing [91]. 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 [92]. Attentional bias can be influenced by emotion and mood [93,94], 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)[95], making it vulnerable to indoor environmental factors.

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 [96]. It acts as an essential cognitive ability in our lives to connect us with the surrounding world. While some reports such as [97,98] distinguish perception from cognition, numerous researchers regard perception as an aspect of overall cognition [99,100]. 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 [101]. Feeling warm or cool is not considered s perception in this study.

Perception may be biased as a function of emotion [102], individual differences (such as different sensitivity to tone sequences [103]), personal context [104], beliefs, and expectations [105]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 [106], visual perception [107], speech perception (also a language function), taste perception [108], touch/haptic perception [109], and olfactory perception [110]. Visual perception is the primary human sense that moderates surrounding information received by the eyes [111]. [112] 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 [113]. 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.

2.3 Memory

Memory is a function that allows the brain to encode, store, acquire, and retrieve knowledge as needed [114]. It is a crucial element of cognition that helps us identify who we are, gain new knowledge, and form a continuity of conscious experience [101,115]. Memory is a component of the information processing system with both explicit and implicit functions [101]. 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 [116]. The memory could be subdivided into as many as 256 different categories [117], going from abnormal memory, through terms such as diencephalic memory, and on to rote memory and sensory memory, and finally to working memory [116]. However, we mainly focus here on broad categories of short-term memory (STM) and long-term memory (LTM) in this study [119].

External stimuli can be converted to memorized information via roughly three steps [120]. First, human beings process stimuli through sensory memory that serves as a brief holding system for the information presented to the various sensory systems [120]. Sensory memory is vital for the listener to integrate incoming acoustic information [112]. Then, the working memory processor encodes the information, keeps it in mind temporarily, and meanwhile searches and activates data from previously-stored memories [121]. Finally, the new information is integrated with and then stored in long-term memory [122].

STM is versatile and supports reasoning and the guidance of decision-making behaviors [123]. When a person is distracted (e.g., by indoor noise or experiencing a cold draft near an exterior window), information is 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 [124]. 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 [120]. Sensory memory is, for example, a vital part of the listener to integrate incoming acoustic information [112].

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 [116]. LTM has a much larger capacity and duration than STM. As such, LTM may be less susceptible to poor indoor environmental quality.

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 [125]. It can be divided into five components, semantics, phonology, morphology, syntax, and pragmatics [126]. Language acquisition is the process by which humans perceive, comprehend, and acquire information from language [127]. Some examples of language functions include word finding, language comprehension, repetition, expression, reading, and writing [128]. 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 [113,129].

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 [130]. 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 [131]. A perception study [130] 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.

2.5 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 [132]. Primary topics investigated in higher order cognition consists of executive function, problem solving, judgment, decision making, planning, and reasoning.

These executive functions are a set of complex cognitive processes that help people manage thought, skills, and necessary behavior, and action to achieve goals [133]. 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 to the requirement of several more fundamentally processes working at the same time to support them [134,135].

Decision making is the cognitive ability to do a selection among several possible alternatives [136]. It is the cognitive process of identifying and choosing options by the decision-makers' cognition, preferences, and values. The environment plays a critical part in the decision-making process [137]. Decision-maker is usually in the process of yielding a solution integrated into the continuous interaction with the environment. Complexity and uncertainty of Environment are factors that influence the result of decision making by resulting in a large number of different possible outcomes [138,139]. The study by Iwona et al. show that decision making was greatly influenced by the environmental complexity. They also concluded the Cynefin as a approach to be a support for making decision [139].

Reasoning is regarded as the cognitive process that solving a problem by establishing logical relationships between different problem elements [140]. It is the central activity in intelligent thinking. General reasoning skills include inferential reasoning, deductive reasoning, analogical reasoning, conditional reasoning, and automated reasoning [141]. Reasoning ability can vary by gender, age, and are affected by the surrounding environments including IEQ [142–144].

People use planning skills to set and achieve goals by developing plans and choosing the appropriate actions based on the anticipation of consequences [145]. 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 [146]. 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 [147].

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 [135]. Previous research found that indoor environmental factors such as lighting, noise, or thermal environment have established effects on these problem solving [38,142,148].

Appendix II

Table A1. *Summary of IEQ on attention*

Reference	IEQ vs Cognition	Sample size & environmental conditions	Measures of cognitive functions	Major findings	Significance level↓
[89]	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
[149]	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
[150]	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
[151]	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.	
[152]	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
[153]	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
[69]	Thermal environment **vs** Attention	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.	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
[87]	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
[88]	Thermal environment **vs** attention	56 subjects (28 males, average age of 24.7 years). The temperature changed in order at 26 ℃, then 29 ℃, then 23 ℃. The effect of elevated air movement with an occupant-controlled fan was investigated for 26 ℃ and 29 ℃.	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 ℃ (p = 0.12) or 29 ℃ (p = 0.37).	0

[154]	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
[155]	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
[156]	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
[157]	Thermal environment **vs** Concentration	26 office workers (46% males, 73% between 31 and 50 years old, 29% under 30 years old); Temperature conditions: 22 ℃ and 25℃.	Feature match test to measure concentration.	The test scores for the concentration test were approximately 137 at 25℃ and 128 at 22℃. No statistical difference was found.	0
[143]	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℃ 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.	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
[158]	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.	
[159]	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
[160]	Thermal environment **vs** Attention	33 students (17 males, mean age of 22.1 ± 2.3 years for all participants); 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. 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
[161]	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
[38]	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 ℃ and 27 ℃; 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
[40]	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
[162]	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-to-noise ratios (SNRs) of stimuli: -5 dB, 20 dB, and quiet condition.	Younger and older subjects identified single words in quiet and two noise conditions (SNR 20 and -5 dB). The cortical area for attention was measured by fMRI.	The fMRI results showed reduced activation in the auditory cortex but an increase in attention-related cortical areas (prefrontal and precuneus regions) in older subjects, especially in the SNR −5 condition.	N/A

		The three sets of stimuli were then normalized to 70 dBA.			
[163]	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
[127]	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
[164]	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
[43]	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	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

		lighting source vs purely direct lighting.			
[165]	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
[160]	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
[166]	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
[167]	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

[168]	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
[169]	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
[170]	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
[171]	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

[⸸] **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 or/and 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 A2. *Summary of IEQ on perception*

Reference	IEQ vs Cognition	Sample size & environmental conditions	Measures of cognitive functions	Major findings	Significance level
[89]	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
[172]	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
[173]	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
[174]	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
[175]	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

[176]	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
[177]	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 or/and 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 A3. Summary of IEQ on memory

Reference	IEQ vs Cognition	Sample size & environmental conditions	Measures of cognitive functions	Major findings	Significance level[‡]
[149]	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
[152]	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
[178]	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
[179]	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

[180]	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
[153]	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
[89]	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
[181]	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
[38]	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 ℃ (p = 0.016). Short-term recall: More words were remembered at 21 °C than 27 °C (p = 0.009).	2

[182]	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
[183]	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
[184]	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
[69]	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
[88]	Thermal environment **vs** Working memory	56 subjects (28 males, average age of 24.7 years); Temperature changed in order at 26 ℃, then 29 ℃, then 23 ℃. The effect of elevated air movement with an	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

		occupant-controlled fan was investigated for 26 ℃ and 29 ℃.			
[157]	Thermal environment **vs** Memory	26 office workers (46% males, 73% between 31 and 50 years old, 29% under 30 years old). Temperature conditions: 22 ℃ and 25℃.	Digit span test was used for memory performance.	The test scores for the digit span test were approximately 7.2 at 25℃ and 7.4 at 22℃. No statistical difference was found ($p = 0.218$).	0
[87]	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
[185]	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
[174]	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
[154]	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
[172]	Thermal environment **vs** Working memory	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.	Visual learning test	Visual learning test results indicated 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

[143]	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 ℃ 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.	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
[159]	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
[173]	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
[158]	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
[38]	Noise **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: 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 ℃	1

				(p = 0.016). But the effect of noise was not significant when the temperature was 21 °C.	
[163]	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
[162]	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
[186]	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
[161]	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	2

				also worse for the chronically noise-exposed children ($p < 0.04$).	
[40]	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
[41]	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
[39]	Noise **vs** Speech prose memory	23 adolescents (9 males, age of 17 years). 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}.	The operation span task was used to assess the participants' working memory capacity. Prose memory was tested by two tasks which were combined by the reading phase and recall phase.	The significant difference in participants' scores on the prose memory task was found between the speech noise condition and 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	1

		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}.		contributed more to individual differences in susceptibility to the effects of aircraft noise on prose memory than to the effects of speech.	
[38]	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
[142]	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
[164]	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

[187]	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
[177]	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
[166]	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
[43]	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
[171]	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 or/and 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 A4.__ Summary of IEQ on language function

Reference	IEQ vs Cognition	Sample size & environmental conditions	Measures of cognitive functions	Major findings	Significance level[↓]
[152]	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
[188]	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
[173]	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
[189]	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
[190]	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).			
[191]	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
[40]	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
[192]	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 room with classroom noise and with background speech.	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

[190]	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
[191]	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
[163]	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

[162]	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
[189]	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
[193]	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
[194]	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

[195]	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
[127]	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
[189]	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
[170]	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

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 or/and 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 A5. *Summary of IEQ on higher order cognitive skills*

Reference	IEQ vs	Sample size & environmental conditions	Measures of cognitive functions	Major findings	Significance level[‡]
[171]	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
[149]	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
[179]	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
[152]	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
[153]	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
[181]	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

[2]	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
[196]	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
[155]	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 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.	1

[159]	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
[88]	Thermal environment **vs** Choice and executive function	56 subjects (28 males, average age of 24.7 years). The temperature changed in order at 26 ℃, then 29 ℃, then 23 ℃. The effect of elevated air movement with an occupant-controlled fan was investigated for 26 ℃ and 29 ℃.	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 ℃ ($p = 0.57$) or 29 ℃ ($p = 0.34$). Similar, using a fan did not significantly affect the performance of a Stroop test at 26 ℃ ($p = 0.12$) or 29 ℃ ($p = 0.37$).	0
[160]	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 ℃; 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).	All types of reaction times in higher temperatures (37 ℃) have been significantly increased compared to those in lower temperature conditions (22 ℃) ($p < 0.05$).	2
[174]	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
[69]	Thermal environment **vs** Conditional reasoning and Visual choice RT	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.	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	Participants performed tasks most quickly at 32 ℃ and lowest at 19 ℃. The variation of response time between 24 ℃ and 27 ℃ was smallest compared with other temperature pairs, and the response time of 27 ℃ was longer than that of 24 ℃ ($p = 0.887$). The large variance of accuracy and speed indicated that there were large	0

			tests. The spatial image was sued for measuring spatial reasoning.	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.	
[38]	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 ℃ and 27 ℃; 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
[183]	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
[185]	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
[172]	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	N/A

				accuracy at the two humidity levels was minimized. No statistical significance was provided.	
[87]	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
[154]	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
[157]	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 ℃ and 25 ℃.	Reasoning skill was used to measure the subjects' verbal reasoning ability. The planning skill was used to test spatial planning performance. The two tests were conducted on the platform of CBS.	CBS test scores of the reasoning skill (p = 0.594) and planning skill (p = 0.114) were not significantly affected by temperature.	0
[143]	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	1

				reasoning performance around a neutral thermal sensation. Planning performance had a highly significant negative linear relationship with TSV and air temperature ($p<0.001$).	
[191]	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
[173]	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 carryover effects were corrected for the measured performance.	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 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.	1
[184]	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 ℃.	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

[38]	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 ℃ and 27 ℃; 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
[197]	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 many solutions as they could think of for the given problem.	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
[198]	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
[199]	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 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	2

			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).	anxiety). Furthermore, these effects were better predicted by perceived control than by noise level.	
[191]	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
[38]	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; Temperature: 21 ℃ and 27 ℃; 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
[142]	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
[187]	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)	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	0

			information about a fictitious employee	as significantly more motivated than the male.	
[159]	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
[160]	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
[166]	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
[200]	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
[171]	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

ˡ**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 or/and 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 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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