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Ten questions concerning dynamic sensory variation in salutogenic building design

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ABSTRACT

In architectural design we are increasingly witnessing a form of salutogenic-washing rhetoric, a marketing-driven tendency to justify design choices by citing alleged health benefits. This article seeks to reclaim the term by anchoring it to Aaron Antonovsky's Salutogenic Model of Health. Rather than a mere intellectual exercise, this analysis challenges the prevailing pathogenic approach to building design, which prioritizes static, comfortable environments aimed at minimizing risk factors and pathogens. In contrast, aligning with human evolutionary physiology, a salutogenic approach emphasizes design strategies that introduce health factors and foster active adaptation within dynamic environments, i.e. spaces that inherently contain stressors, which can themselves be leveraged to develop resistance resources. Within this framework, we explore ten key questions on how sensory variability, both in space and time, can serve as one of the key factors in health-promoting building design. Bringing together experts in architecture and the built environment, neuroscience and immunology, this discussion, rooted in Antonovsky's theory, examines how variations in thermal, visual, acoustic, olfactory, gustatory, and tactile environments can enhance health and positively impact the immune system, based on the identification of pathways linking sensory inputs to neuro-immune modulation. The study shows that available evidence from animal and human studies on the beneficial neuroimmune effects of sensory variation is uneven across domains, with stronger support in the visual and thermal domains. Ultimately, this leads to a proposed agenda for future research and practice in salutogenic building design focusing on multisensory dynamic variation in the indoor built environment.

1. Introduction

The *healthy buildings* movement has, especially since the COVID-19 pandemic, shone a spotlight on the relationship between buildings and health and, not least, on its consequences for the performance and productivity of building occupants [1]. Linked primarily to the issues of proper ventilation and air quality [2], the movement has forcefully highlighted that “The decisions we make today regarding our buildings will determine the collective health of people and the planet now and for future generations” [1]. However, looking closely at the proposed solutions, it becomes clear that the focus remains largely on the causes of sick building syndromes, that is, on what makes occupants ill during their prolonged stays indoors [3,4]. As a result, the real goal is not to make buildings, or their users, healthy, but rather to prevent the occupants from becoming ill. Despite good intentions, the ultimate aim of this field of research and practice is essentially to ensure that people are *okay* and productive: an approach that can be defined as pathogenic, similar to that pursued in the sphere of medicine. Recently, the concept of healthy buildings has expanded to include aspects related to the affective impact of buildings on occupants and aesthetics, in an effort to make them feel “well,” including even broader impacts on society and the environment, according to frameworks recently proposed [5–7]. In the literature about healthy buildings, the topic has often been accompanied by the term *salutogenic*. As stressed by Golembiewski [8] and Mazzi [9], this has been used often in the literature more as a buzzword in a kind of “salutogenic-washing” narrative, at a time when comfort,

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well-being, and sustainability alone were no longer enough to market a new product. Yet the term is intrinsically tied to a very specific theory, that of the sociologist Aaron Antonovsky [10].

In this work, we aim to reconnect the concept of salutogenesis with Antonovsky's theory and demonstrate its relevance to building design through the case study of sensory variability: the design of buildings that dynamically engage occupants and their senses across space and time, enabling them to develop resistance resources to face external stressors. Recent discussions on sensory variability often frame it as a way to make environments more pleasant and to enhance well-being, in contrast to the prevailing trend of creating static spaces [11,12]. The notion of architecture that offers a sequence of varied and stimulating settings is not new: it resonates with ideas of environmental complexity [13], environmental diversity [14], and design for contrast in the sonic environments [15], as well as with research on thermal alliesthesia [16–18] and circadian lighting [19,20], which belong more directly to the field of indoor environmental quality, and will be further discussed below. However, what remains unexplored is the link between sensory variability and the health of people exposed to such dynamic environments.

By bringing together a multidisciplinary team of built environment scientists, immunologists, and neuroscientists, and inspired by Antonovsky's writings, we sought to outline the evidence supporting a salutogenic building design through dynamic environments, one that creates occupant health through the dynamic variation of environmental sensory stimuli. To this end, we first introduce the concept of salutogenesis and Antonovsky's theory (Q1), then examine how it can be applied to the study and design of the built environment (Q2), what it implies beyond design for comfort or well-being (Q3), and finally describe the biological foundations linking sensory variation to the immune system (Q4). We further explore how these mechanisms unfold across different senses by reviewing the available literature (Q5 for thermal variation, Q6 for visual variability, Q7 for soundscape, Q8 for olfactory and gustatory stimuli, and Q9 for the tactile environment). From this, we derive a set of recommendations for future building research and design (Q10), aimed at being salutogenic-driven in the most authentic sense of the word.

2. Questions

2.1. *Question 1: what is the origin of the term "salutogenesis"?*

The neologism salutogenesis ("the origins of health" [10]) was coined in 1979 by Aaron Antonovsky to describe the mindset required to answer the core research question underpinning his work: What makes people healthy? Antonovsky criticized the pathogenic approach traditionally taken in health research, which is based on a dichotomous classification of individuals as either sick or healthy. According to this model, "the human organism is a splendid system, a marvel of mechanical organization, which is now and then attacked by a pathogen and damaged—acutely, chronically, or fatally" [21]. Curative medicine focuses on those who are already sick; preventive medicine focuses on those at risk of becoming sick. In both cases, the emphasis is on pathogens and risk factors, leaving little room for a proactive promotion of health. In contrast, Antonovsky proposed a continuum model, moving beyond the binary of health vs. illness, where each individual is located somewhere along a "healthy/dis-ease continuum" [21]. Therefore, the salutogenic question is: How can we understand the movement of people toward the healthy end of this continuum? This question concerns everyone and suggests that health is not only about avoiding or reducing risk factors but also about identifying and reinforcing factors that promote it, i.e. salutary factors [21]. Antonovsky also challenged the notion of balance (homeostasis) as the natural state of the human organism. Instead, he introduced the idea that the human condition is one of heterostatic disequilibrium, a central tenet of the salutogenic orientation [22]. In this view, disorder, illness, and entropy are not exceptions but rather the norm. Exposure to stressors does not necessarily lead to stress or illness. Stressors trigger tension, but if that tension is successfully managed or resolved, it needs not be harmful: in fact, it may even be beneficial or "salutary." The focus thus shifts to equipping individuals with the resources needed to manage tension and cope effectively with the inevitable stressors of life, that is, to enhancing human resilience in its three components (toughness, ability to cope, and capacity to recover) according to Schweiker's modern conceptualization [23]. Antonovsky called these resources Generalized Resistance Resources (GRRs): characteristics of individuals, communities, or environments that enable successful coping and active adaptation. What all GRRs have in common is that they foster a person's ability to perceive their internal and external environments as comprehensible, manageable, and meaningful. This overall orientation is referred to as the Sense of Coherence (SOC) [21]. According to Antonovsky's theory, the strength of a person's SOC is a key determinant of their movement toward the health end of the continuum. When facing a stressor, an individual or community with a strong SOC is more likely to be motivated to cope (meaningfulness), believe the situation is understandable (comprehensibility), and feel confident that the necessary resources are available (manageability). If scales have been proposed to measure the SOC [22], the theoretical discussion around the study of the construct is still ongoing.

The salutogenic approach thus shifts the direction of health research away from the disease-centered, risk-reduction paradigm, typical of the pathogenic model, even within health promotion itself, which Antonovsky argued was still too often rooted in pathogenic thinking [21]. His ideas are addressed not only to fellow medical sociologists but also to sociologists, psychologists, community planners and crucially, to architects and all those who seek to understand and strengthen the adaptive capacities of human beings [10]. As it will be discussed in the following section, this has important implications for the design of the built environment.

2.2. *Question 2: how does the salutogenic approach apply to the design of the built environment?*

If GRRs are defined as "any characteristic of the person, the group, or the *environment* that can facilitate effective tension management" [10], then it follows that the surrounding environment, and the way it is designed, plays a significant role in moving toward the health end of Antonovsky's health ease/dis-ease continuum. Several scholars have examined how a salutogenic approach can be applied to architecture, with some explicitly referencing Antonovsky's work. Notably, Dilani and Golembiewski have explored salutogenic design in the built environment through the lens of the Sense of Coherence (SOC), identifying environmental qualities that may support an individual's orientation toward the world in terms of meaningfulness, comprehensibility, and manageability [8,24,25]. For example, Golembiewski associates manageability with safe, barrier-free, person-centred design that meets user needs [8], such as ensuring adequate indoor environmental quality [25]. Comprehensibility is linked to principles of readability, simplicity, and predictability, for instance, in wayfinding [8]. Meaningfulness is tied to occupant engagement through architecture that employs symbolic language [8]. For a full account of these associations, the original works of these authors should be consulted. It should be noticed that in Antonovsky's original formulation, these dimensions refer to an individual's internal orientation rather than to external environmental attributes, such as architectural features. It is therefore uncertain whether enhancing specific physical characteristics, such as ease of wayfinding, can directly strengthen the hypothesized corresponding SOC dimension in individuals, such as comprehensibility. As Mazzi has noted [9], there is a lack of methodologies for assessing the effectiveness of the design strategies proposed in the literature, which often stem more from professional experience than from empirical evidence. Although the literature increasingly frames architecture as a tool for health promotion [26], ambiguity in the use of health-related terminology and in the distinction between health outcomes intended by designers and those empirically measured has resulted in limited and fragmented evidence on the topic, even within the healthcare sector [27], where greater conceptual clarity might be expected. In this paper, we do not seek to map specific environmental features to individual SOC dimensions. Instead, we apply the broader principles of salutogenic theory to architectural practice, grounding our approach in scientific evidence that links these principles to health outcomes, particularly through their effects on the immune system. In this context, we focus specifically on sensory variability as a key factor influencing immune responses and overall well-being. This emphasis provides a tangible link to architectural practice, as sensory variability can be operationalized through strategies such as dynamic lighting, thermal and acoustic zoning, and passive ventilation strategies, approaches widely recognized in building design, even if not previously framed within a salutogenic perspective, which actual salutogenic effects remain to be quantified through future research (see Q10 for further discussion).

Reframing Antonovsky's question for the built environment, we ask ourselves: How can we design spaces that provide occupants with generalized resistance resources capable of promoting health? This perspective underscores the fundamental role of architecture in shaping human health, succinctly expressed by Farrow's provocative question: *"What if we could construct health?"* [26].

This perspective shifts architectural research and practice from solely reducing risk factors to actively enhancing salutary factors. In environmental design—whether thermal [16], visual [28], auditory [29], or olfactory [30]—there is a growing movement toward creating spaces that are not merely neutral or non-disturbing but genuinely pleasurable. This shift influences not only the design of post-occupancy evaluation tools (by including measures of positive experiences) [31–33] but also experimental protocols in research and the design of built interventions themselves.

A further consideration is the integration of features that enable active adaptation to environments in dynamic, non-steady-state conditions. This is increasingly relevant in the context of climate change, where adaptation, defined by the Intergovernmental Panel on Climate Change as "the process of adjustment to actual or expected climate and its effects in order to moderate harm or take advantage of beneficial opportunities" [34], has become a key design objective. Providing opportunities for user control [35], such as through natural ventilation [36] or Personal Environmental Comfort Systems (PECS) [37–40], is known to facilitate successful tension management under challenging environmental conditions and heterostatic disequilibrium.

While active adaptation and sensory variability may not always result in conventionally "comfortable" environments, salutogenic theory reminds us that its focus is not on "keeping people well" [21] in the narrow sense. This prompts a crucial distinction: What does it mean to design for health promotion rather than merely for comfort and pleasurable environments?

2.3. Question 3: how does building design for health promotion differ from design for comfort and well-being?

Since the onset of HVAC systems, indoor environments have been designed according to standards that prioritize neutrality and comfort [41,42], typically defined as a condition of mind in which one feels relaxed and free from pain [43]. ASHRAE Standard 55, for instance, defines thermal comfort as "the condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation" [44]. In the thermal domain, comfort has often been evaluated—and, more importantly, operationalized—through standards and practices based on Fanger's PMV–PPD and the adaptive comfort model [45–49], primarily to prevent discomfort and minimize dissatisfaction. However, such implementations have frequently aimed at maintaining narrow, constant environmental conditions to avoid stressors, thus implying an inherently limited and pathogenic approach, eventually leading to environmental monotony or "boredom" [50]. Conversely, focusing on more dynamic environments could foster more positive health outcomes, aligning with the salutogenic model [11,41].

Beyond traditional comfort standards, recent literature has expanded toward holistic frameworks addressing health and well-being in buildings. Research on human-building interaction and dynamic comfort highlights the importance of variability and user control in promoting delight and improving the user's experience [11,51–54]. This is reflected in building certification protocols, with the WELL Building Standard incorporating metrics for better addressing occupant experience [7]. Recent research emphasizes the need to move beyond traditional static comfort models, towards more integrative frameworks that consider these elements, linking comfort with "health and well-being" [41,52]. Notably, Heschong's work partially anticipated this evolution by advocating for environments that move beyond neutrality and embrace thermal and visual experiences as sources of pleasure and engagement [55,56], paralleling more recent developments in indoor soundscape and smellscape research within the acoustic and air-quality domains [29,32,33]. These ideas resonate with the concept of alliesthesia [16,18,57] and provide an early foundation for dynamic sensory variation. Moving from comfort to well-being would be a step forward, but it still lacks the essential link to health.

How is design for well-being different from the design for health? The distinction between well-being and health is slippery and widely debated in the literature, to the extent that many scholars cautiously frame them together as "health and well-being" [58]. Referring to other works for a detailed review and to acknowledge the lack of consensus on these two concepts [59], we adopt a pragmatic distinction: we consider well-being as a construct grounded in subjective judgments [52], whereas health is treated as an objective and clinically measurable state, encompassing both physical and mental conditions [58]. In this interpretation, design for well-being seeks to create pleasant environments and may not always align with design for health. To illustrate, a loud environment playing our favorite music might make us feel well, yet simultaneously damage our health. Similarly, many of the design proposals for "healthy buildings", when not even pathogen-focused, are in fact aimed at creating pleasant environments, leaving the connection with biological systems, such as the immune system, unaddressed. This conceptual distinction is depicted in Fig. 1. Conversely, a salutogenic approach does not necessarily aim to make us feel well at every given moment, but rather to provide the GRRs that orient us toward the health pole of the ease/dis-ease continuum [10,21,22]. Building on Antonovsky's theory, we propose that exposure to environmental stressors, when carefully controlled and appropriately dosed, can be beneficial. According to the hormesis model of psychosocial stress [60], organisms develop resilience through preconditioning: an adaptive process in which mild stress strengthens physiological and psychological systems [61,62], while an environment that places no demands on us is a stressor

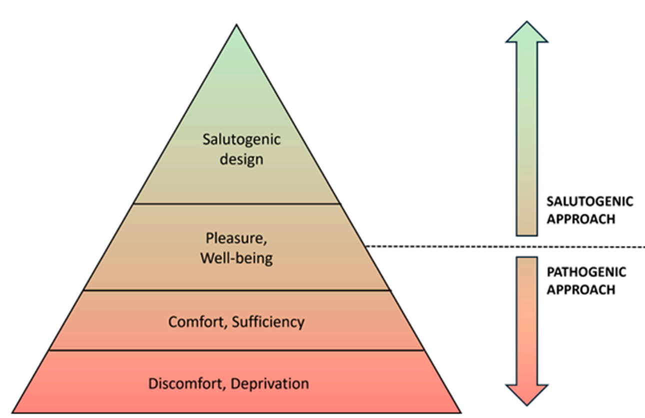

Fig. 1. Spectrum of indoor design targets: re-interpretation from spectrum of occupant experience [11,42] and ranges of environmental comfort [69].

in itself, following the underload concept [10]. The adaptive process of preconditioning fosters "eustress", defined as "the healthy, positive, constructive outcome of stressful events and the stress response" [63,64]. Rhythmic variations in the built environment or rhythm-mimicking dynamic environments can further align with natural biological patterns, such as circadian cycles and other vital processes [65,66], which are often suppressed in today's static indoor settings. This perspective, consistent with salutogenic design, resonates with the WHO's definition of health as "a state of complete physical, mental and social well-being, and not merely the absence of disease or infirmity" [67]. Whereas the concept of healing design [68] has traditionally focused on mitigating illness or facilitating recovery, thus still reflecting a pathogenic orientation, salutogenic design shifts the emphasis toward proactively fostering health, cultivating environments that build resilience and prepare individuals to face future challenges. Extending the salutogenic paradigm to the science of the built environment (Q1 and Q2), our hypothesis is that dynamic sensory stimuli can act as health-promoting factors, training individuals' psychophysiological and neurological responses to environmental stressors (in line with the hormesis model). This, in turn, may enhance central nervous system plasticity and strengthen immune defenses against external threats, according to the dynamics outlined in Q4.

2.4. Question 4: how do sensory stimuli modulate the functioning of the immune system?

Among the multiple determinants of human health, the continuous interplay of physiological systems plays a central role in supporting adaptation to internal and external demands. In such a context, the nervous and immune systems are central players. Although traditionally studied as separate entities, growing evidence shows that they are tightly interconnected, enabling coordinated responses to internal and external challenges (see Leunig et al., 2025, for a review [70]). This crosstalk is based on neurotransmitters, nerve impulses, hormones, and cytokines produced in response to sensory stimuli. Light, sound, temperature, and olfactory, gustatory, and tactile inputs can modulate stress responses and inflammatory activity, alongside social stressors, metabolic states, and immune challenges such as infection. This is shown by experimental and clinical observations, which indicate that enriched and varying sensory environments can sustain a more robust immunity and prevent chronic inflammation (see Casares et al., 2024, for a review [71]). Therefore, the way an environment stimulates the senses may represent an important contextual factor influencing health-related physiological regulation. To appreciate the connection between human health and environmental variability, it is useful here to outline the basic working principles of both the immune and nervous systems and the links through which they communicate. This will provide the conceptual basis for the subsequent questions, which will focus on individual senses.

The immune system operates on two complementary levels. Innate immunity provides the first line of defence, with physical barriers and effector cells such as macrophages, neutrophils and natural killer (NK) cells that provide a rapid response to block infectious agents. Innate immune cells secrete cytokines following the encounter with a microbe (e.g., a bacterium or a virus) and promote inflammation, a condition that maximises the anti-microbial response and activates the second line of defence, the adaptive immunity. The latter is a slower but highly specific and long-lasting response mediated by B cells, which produce antibodies, and T cells, which directly kill infected targets and organise the specific anti-microbial response. A fine control of inflammation and adaptive immunity is crucial since sufficient strength is required to eliminate infectious agents, but an excessive or prolonged response results in tissue damage, chronic inflammation or autoimmunity. Several signals are therefore fundamental to control the development, the activity and the lifespan and replication of immune cells and ensure a balanced response. Crucially, many of these regulatory signals originate from the nervous system, allowing immune activity to be modulated not only by pathogens but also by non-infectious environmental and psychosocial stimuli that do not physically enter the body [72–75].

This neuroimmune organization is particularly relevant for IEQ (Indoor Environmental Quality), as sensory stimuli such as light, sound, temperature and touch influence immune regulation indirectly through neural and endocrine pathways rather than through direct immune challenge. The organisation of the immune response, as well as the development of immune cells, occurs in lymphoid organs (e.g., bone marrow, thymus, spleen, lymph nodes, and the gut lymphoid tissue), which are present throughout the whole human body. The lymphoid tissues are directly innervated by sympathetic and parasympathetic nerve fibres, establishing neuroimmune synapses that deliver neurotransmitters and neuropeptides capable of modulating the activity of immune cells; interestingly, these nervous signals can both activate or inhibit the immune response. At the same time, the nervous system regulates the release of hormones, which powerfully modulate the immune cell activity [76–78]. Among these, a prominent role is played by cortisol, a corticosteroid produced by the adrenal gland under the control of the sympathetic nervous system [79]. Cortisol binds the glucocorticoid receptors on immune cells, and leads to suppression of inflammation, inhibition of T- and B-cells, and mobilisation of neutrophils. Of note, cytokines such as interleukin 1 (IL-1), interleukin 6 (IL-6), and tumor necrosis factor α (TNF-α) released by the immune cells feed information back to the brain through the bloodstream and via the vagus nerve. This feedback induces a bidirectional neuroimmune regulatory loop and results in behavioural changes such as fatigue, reduced appetite and increased sleep [80]. These pathways provide the mechanistic basis through which sensory characteristics of the built environment can influence immune function without involving direct exposure to pathogens or tissue invasion.

In the nervous system, the limbic system and the hypothalamus play a central role in providing signals to modulate the immune system. Sensory stimuli (light, sound, smell, temperature, pain, and visceral signals from the internal organs) reach the limbic areas of the brain and the hypothalamus via specific sensory pathways. In particular, visual and auditory inputs are relayed through the thalamus; olfactory signals project directly from the olfactory bulb to the amygdala and hippocampus; somatosensory, thermal, and pain signals ascend through the spinal cord and brainstem nuclei before reaching hypothalamic and limbic centres. Collectively, in response to sensory signals, the hypothalamus secretes hormones that regulate the activity of the pituitary gland and induce the adrenal gland to produce corticosteroids, including the aforementioned cortisol: this pathway is called hypothalamus-pituitary-adrenal (HPA) axis. In parallel, as mentioned above, the autonomic nervous system, also controlled by the hypothalamus, directly innervates lymphoid tissues with its sympathetic branch (which activates immunity via adrenergic stimuli) and the parasympathetic counterpart (which dampens inflammation through anti-inflammatory cholinergic signals released by the vagus nerve) (Fig. 2) [81].

How each sensory stimulus influences immunity has been well established and constitutes the scientific basis of this article. It is useful to keep in mind that the relationship between stimuli and response is not linear. Both overstimulation and sensory deprivation can be detrimental. Accordingly, persistent stress, particularly under chronic exposure conditions, has been shown to suppress immune function in both animal models and human studies, whereas monotonous or environmentally impoverished conditions, primarily studied in animal models and supported by indirect human evidence, have been associated with weakened neuroimmune communication over prolonged time scales (reviewed in [79]). Human evolution occurred in environmental conditions that rarely remained constant: light changed from dawn to dusk, air temperature fluctuated with wind, sounds varied continuously, and scents shifted with vegetation and humidity. Across evolutionary time, the nervous and immune systems adapted to such variability; however, the physiological consequences of environmental change are not

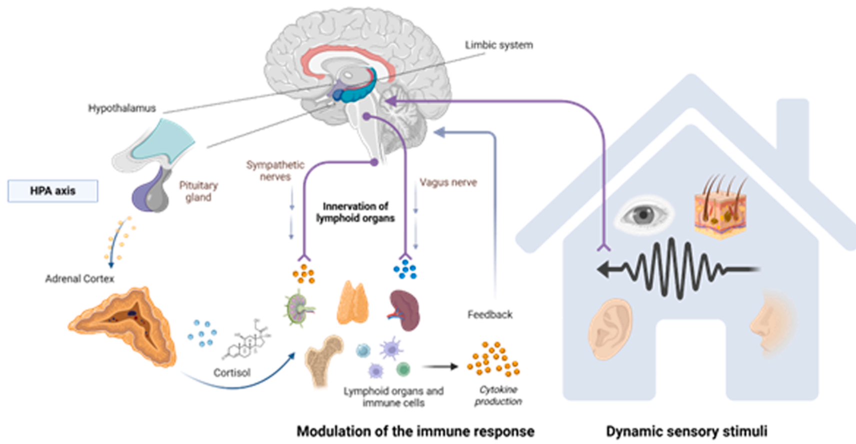

Fig. 2. Pathways linking dynamic variability of sensory stimuli to neuro-immune modulation. The variability of sensory stimuli from the external environment (light, sound, odor, temperature, tactile and gustatory inputs) are perceived by specialized sensory organs and transmitted to the limbic system and hypothalamus. These brain centers integrate the information and modulate immune function through the activation of two major pathways. (1) The hypothalamic–pituitary–adrenal (HPA) axis, which culminates in cortisol release from the adrenal cortex; cortisol binds glucocorticoid receptors on immune cells, generally suppressing inflammation and adaptive immune responses. (2) The autonomic nervous system, which directly innervates lymphoid organs; the sympathetic branch releases catecholamines that can activate or suppress immune cells depending on receptor context, while the parasympathetic branch via the vagus nerve activates cholinergic anti-inflammatory pathways. Cytokines released by immune cells (e.g., IL-1, IL-6, TNF-α) provide feedback to the brain, reinforcing a bidirectional communication loop that regulates stress responses, behavior, and immune activity.

uniform, as modest and well-dosed departures from equilibrium may elicit eustress and support adaptive regulation, whereas excessive, unpredictable, or uncontrollable variation can instead provoke distress [82].

Experimental evidence confirms these links. Mice housed in enriched environments with toys, running wheels and social companions show reduced neuroinflammation, enhanced neuronal plasticity and stronger peripheral immune responses, compared with those in barren cages [83,84]. These findings provide mechanistic support for the role of sensory and motor variability in shaping neuroimmune regulation. In humans, observational and interventional studies suggest associations between exposure to natural environments and changes in inflammatory markers or immune-related parameters; however, systematic reviews highlight substantial weaknesses in study design, including small sample sizes, limited controls, and uncertainty regarding effect size, duration, and reproducibility [85,86]. Consequently, human evidence should be regarded as suggestive rather than conclusive.

From a physiological standpoint, why should exposure to varying, rather than constant, sensory stimuli be beneficial? The answer lies in the observation that biological regulation is known to rely on variation and rhythm rather than constancy. An illuminating example supporting this concept is the well-established finding that glucocorticoid secretion through the HPA axis is not continuous but occurs in pulsatile ultradian rhythms, a phenomenon documented across a large body of experimental work in both animal models and humans, as reviewed in Lightman and Conway-Campbell (2010) [87]. In this context, an oscillatory pattern prevents downregulation or desensitization of glucocorticoid receptors, which are bound by cortisol. Accordingly, diminishing or disrupting these rhythms is linked to dysfunctional stress responses, indicating that variability is not just beneficial but also intrinsic to physiology. Similarly, sensory stimuli that alternate (e.g., varied light, sound, temperature) avoid “sensory adaptation” or habituation and keep downstream regulatory circuits (neural, endocrine, immune) responsive. Indeed, theoretical models of habituation show that constant stimuli produce diminishing information gain, whereas variability preserves system responsiveness [88]. In this light, enriched environments and novel sensory inputs are necessary to counteract sensory adaptation and habituation by continually engaging neural circuits [89]. Environmental variability, as further discussed in the following questions, becomes necessary to train the body and help maintain a healthy immune balance and adaptability.

The pathways described here establish a biologically plausible framework through which sensory stimuli may influence immune regulation; however, as described in the next questions, the extent to which such neuroimmune modulation translates into durable, clinically relevant health outcomes in humans remains unevenly supported and highly dependent on sensory domain, exposure context, and study design.

2.5. *Question 5: how does thermal variability contribute to health?*

In the built environment, thermal comfort has long been regarded as a design objective, frequently presented as a state of low thermal stress (see Q3). Nonetheless, the human thermoregulatory system evolved by developing the crucial mechanism of temperature adaptation in dynamic natural settings. Reintroducing such variability indoors may engage physiological and neuroendocrine processes associated with adaptive capacity and metabolic regulation, which can also actively promote well-being [11,54].

Principles established by the adaptive comfort theory [47,48] show that occupants actively adapt to changing conditions. While these models primarily address comfort, acceptability and related thermophysiological drivers, our focus on immunological effects extends the rationale for variability beyond comfort, toward health promotion. A fundamental concept in appreciating the importance of thermal variation is alliesthesia, i.e. the notion that the pleasure experienced from thermal stimuli is contingent upon the internal state of the body [17,18,90]. For instance, cool air is considered to be pleasant when someone is suffering from hot temperatures. By allowing users to navigate between areas with varying temperatures or to sense subtle changes over time, buildings that integrate spatial or temporal thermal gradients can improve this experience and encourage bodily awareness and engagement. How is this connected to people’s health?

Experimental evidence, particularly from animal models and short-term human exposure studies, suggests that moderate thermal variability engages thermoregulatory, metabolic, and autonomic responses consistent with adaptive capacity. Consistent with this, animal studies have shown that mild cold exposure modulates immune function by altering the phenotype and activity of multiple immune cell populations, including dendritic cells, γδ T cells, and thymic lymphocytes, indicating that departures from thermoneutrality can directly engage immune regulatory pathways [91–93]. In human experimental studies, exposure to mild cold has been associated with increased NK-cell activity, a response that is mechanistically linked to immune surveillance [94]. Conversely, a large body of literature has revealed the molecular role of heat shock proteins (HSPs), which are activated by heat exposure and operate as molecular chaperones that prevent protein misfolding, promote cellular repair, exert anti-inflammatory and cytoprotective effects, and are thereby linked to tissue resilience. As seen in animal models, HSPs promote immune tolerance and protect against autoimmunity [95–98]. Observational studies in humans confirm that excursions to mild cold and warm conditions can have a positive impact on weight loss, as well as glucose metabolism, with potential implications for type 2 diabetes and cardiovascular conditions, though results should be confirmed by further studies involving larger cohorts and control groups [54,99–101]. Furthermore, studies in mice show an association between increased exposure to thermally neutral conditions and increased levels of fat tissue and accelerated metabolic inflammation, with possibly negative health consequences in the long term [102,103]. Conversely, studies in humans have shown that brown adipose tissue (BAT) is physiologically activated by mild cold (16 °C) exposure, thus increasing energy production and glucose metabolism. Such metabolic activation is linked to improved sensitivity to insulin (the hormone controlling blood glucose levels) and to decreased systemic inflammation, both crucial for an improved immune system function [104,105]. In line with these observations, hormesis, i.e. the process by which a mild environmental change or stressor induces adaptive biological processes that increase overall resilience, was observed in animal studies to be influenced by periodic thermal stress [106]. Thermal stimuli also activate the autonomic nervous system and affect cortisol regulation. In particular, controlled cold-exposure paradigms such as cold-face or cold-water immersion have been shown in human studies to increase vagal tone and blunt cortisol responses, reflecting a shift toward parasympathetic dominance and reduced HPA-axis activity [107–109]. Mechanistically, this can be explained by the stimulation of skin sensors that send signals to the hypothalamus. This activates the autonomic nervous system and reduces the activity of the HPA axis. As a result, vagal tone increases, which lowers inflammation through acetylcholine signaling on immune cells, while basal cortisol levels decrease, reducing chronic immunosuppression [108,109]. Together, these findings suggest a modulation of inflammatory tone and immune responsiveness consistent with adaptive regulation. These findings are consistent with the notion that controlled environmental stress augments health by stress-testing physiological systems. In addition, from the psychological perspective, temperature variability could have a positive impact by enhancing the feeling of agency and improving bodily self-awareness, as long as the users have an element of control (i.e., operable windows, room fans, or clothing layers). This type of sense of control can enhance the acceptability of thermal variability and amplify the effects of alliesthesia [54], while also being positively associated with lowered stress reactivity and improved regulation of the immune system [110]. It should also be noted that thermal perception is influenced by factors such as age, gender, health status, sensory sensitivity, and cultural expectations [111–113]. These differences affect not only comfort thresholds but also physiological responses to thermal variability, highlighting the need for personalized strategies in salutogenic design.

In conclusion, the benefits of thermal variability on human neuroimmune function are supported by evidence in the literature, though current evidence is largely based on short-term physiological and mechanistic studies, and further longitudinal and field-based research is needed to substantiate long-term health effects (see Q10 and Table 1 for a more detailed discussion). Nevertheless, the incorporation of thermal variability in building design offers a salutogenic alternative to the traditionally static definition of thermal comfort. Rather than attaining the narrow "thermoneutral zone", designers might instead foster situations that support dynamic thermoregulation, metabolic activation, and

Table 1
Strength of evidence from animal and human studies on the neuroimmune effects of sensory variability. Poor, moderate, and strong evidence is qualitatively defined on the basis of the available literature.

Domain	Strength of evidence from animal studies	Strength of evidence from human studies	Key references
Thermal	Strong. Departures from thermoneutrality engage immune and autonomic pathways. Mild cold exposure mobilizes immune cells (including NK-cells) and alters immune cell phenotype via sympathetic and metabolic mechanisms. Heat exposure induces heat-shock proteins (HSPs), which exert immunomodulatory effects by enhancing antigen presentation, regulating cytokine signaling, and promoting immune tolerance. Chronic housing at thermoneutrality alters immune–metabolic balance and favors inflammatory phenotypes.	Moderate. Regular mild heat exposure induces thermophysiological adaptations and improves blood pressure, endothelial function, and arterial stiffness, while repeated hot-water immersion shows improved glycemic control in type-2 diabetes. Acute cold exposure paradigms (e.g., cold-face test, cold immersion) modulate autonomic and neuroendocrine responses, including increased vagal tone and blunted cortisol secretion. Short-term cold exposure is associated with transient changes in immune-cell activity. Repeated mild cold exposure activates brown adipose tissue and improves metabolic and inflammatory profiles with indirect relevance for immune regulation.	Animals: [91–93, 95–98,102, 103,106] Humans: [54,94, 99–101, 104,105, 107–109]
Visual	Strong. Light–dark cycles and circadian entrainment exert strong regulatory control over immune function through cell-intrinsic circadian clocks, the suprachiasmatic nucleus, and downstream neuroendocrine and autonomic pathways. Disruption of circadian rhythms alters immune cell trafficking, cytokine production, and adaptive immune responses. Evidence for visual environmental enrichment effects on neuroinflammation exists primarily within multisensory enrichment paradigms.	Strong (circadian cycle) and Limited–Moderate (other visual features). Daylight and short-wavelength light entrain circadian rhythms, regulating cortisol and melatonin cycles with downstream effects on immune cell function. Circadian disruption (e.g., artificial light at night) is associated with impaired vaccine responses and increased inflammatory markers. Evidence linking other aspects of visual variability (e.g., views, spatial complexity, color) to immune outcomes is indirect and primarily mediated through stress reduction and autonomic regulation rather than direct immune endpoints.	Animals: [127,130, 137–141] Humans: [126,127, 129, 131–138, 140,142, 147]
Soundscape	Limited–Moderate. Chronic noise exposure induces stress-related immune suppression, elevates cochlear cytokines (e.g., IL-6), increases immune-cell infiltration, and triggers neuroinflammation in auditory and limbic regions. Evidence for	Limited. Sound exposure is linked to stress physiology rather than direct immune outcomes. Environmental noise is associated with increased catecholamines, sleep disruption, and stress-related health effects, while music and natural sounds can reduce stress and support recovery. There is limited direct	Animals [162–164] Humans: [161,165, 173–175]

(continued on next page)

Table 1 (*continued*)

Domain	Strength of evidence from animal studies	Strength of evidence from human studies	Key references
	beneficial immune effects of variable or naturalistic sound exposure in animals is suggestive rather than conclusive.	evidence linking soundscape variability in buildings to long-term immune outcomes.	
Olfactory and gustatory	Moderate. Specific odorants (e.g., phytoncides) modulate immune responses, including reductions in pro-inflammatory cytokines and enhancement of NK-cell activity. Olfactory deprivation alters immune development and impairs immune-regulatory pathways, supporting a role for continuous sensory input in immune homeostasis.	Limited–Moderate. "Forest bathing" and phytoncide exposure are associated with increased NK-cell activity and reduced stress hormones, which arise from complex multisensory and behavioral exposures. Pleasant odors reduce cortisol and anxiety via limbic–HPA–autonomic pathways. There is limited evidence linking olfactory or gustatory variability in buildings to immune outcomes, with individual and cultural variability.	Animals [177,178] Humans: [176,177, 179,180, 183, 185–187]
Tactile	Moderate. Environmental enrichment correlates with reduced neuroinflammation, altered microglial phenotypes, and strengthened peripheral immune responses. These effects typically arise from multisensory enrichment, with tactile input acting as one contributing component.	Moderate. Tactile stimulation (e.g., touch, massage) increases vagal tone, reduces cortisol, and can lower inflammatory markers. Proprioceptive and movement-related stimulation (e.g., physical activity) has well-established anti-inflammatory effects and improves immune surveillance. Evidence specific to architectural tactile variability remains indirect.	Animals: [178,188, 192,193] Humans: [188–191, 194–199]

stress restoration processes that are closely linked to immune competence.

2.6. Question 6: in what ways can visual variability enhance health?

Sight is the most powerful sense in humans, having the greatest impact on the perception of space, time, and emotional state [114]. Lighting standards primarily aim to support visual tasks, with EN 12464-1 [115] specifying fixed minimum values for illuminance, uniformity, glare, and color rendering index based on the environment type. However, the literature increasingly emphasizes aspects like daylight availability, view quality, and non-visual effects [28,116–123], only partially addressed by EN 17037 [124]. Besides the positive psychological benefits of connection with nature, especially where natural and biophilic elements are present [125], exposure to daylight has other advantages. These advantages can be associated with variability and rhythm, and are aligned with a salutogenic design approach. Indeed, visual variability (i.e., differences in color, light, contrast, texture, and spatial complexity) is considered to be central to the enhancement of psychological wellbeing, supporting circadian regulation, and influencing neuroendocrine and immune function [126].

Accordingly, evidence from animal models and controlled human laboratory studies indicates that dynamic visual stimuli, particularly variations in light intensity, spectrum, and timing, modulate circadian regulation and stress-related neuroendocrine pathways that are known to influence immune function. In humans, these effects are primarily supported by associations with circadian alignment, hormonal rhythms, and short-term physiological markers [127], though direct evidence linking visual variability in buildings to long-term immune or clinical health outcomes remains limited.

One of the key ways in which visual stimuli affect physiology is the entrainment of circadian rhythms. The stimulus of moving natural light (which varies in intensity, direction, and spectral composition during the day), regulates the cyclic synthesis of melatonin and cortisol hormones through a subpopulation of retinal ganglion cells that directly respond to short-wavelength blue light (∼480 nm) stimulation (intrinsically photosensitive retinal ganglion cells, ipRGCs) through a photoreactive protein (melanopsin) [128–132]. The suprachiasmatic nucleus (SCN) of the hypothalamus, in turn, regulates immune function via circadian control of the hypothalamic–pituitary–adrenal (HPA) axis and the autonomic nervous system (ANS). These pathways modulate the daily rhythms of cortisol and sympathetic–parasympathetic balance that govern immune-cell trafficking, cytokine production, and inflammatory tone. Human studies show that short-wavelength blue light regulates sleep and waking cycles and modulates heart rhythm, alertness, metabolism, immune response and cognitive performance [133]. Therefore, inappropriate light exposure (e.g., artificial light at night) disrupts circadian rhythms and can lead to sleep disturbances and health disorders [134–136]. Accordingly, a lack of visual variability, like under situations with dominance of static artificial lighting, may disrupt the circadian signaling and compromise immunocompetence. As stated above (2.4 - Question 4), light entrains circadian rhythms through the SCN, modulating daily cortisol and melatonin cycles and influencing immune responses [137]. The human immune system itself follows strong circadian oscillations, with daily rhythms in leukocyte trafficking, cytokine secretion, and antibody responses [138]. Consistent with this, animal studies have demonstrated that immune cells possess intrinsic circadian clocks that regulate lymphocyte trafficking and adaptive immune responses, with circadian control of migratory cues establishing lineage-specific patterns of immune-cell homing across tissues [139,140]. Light-driven circadian entrainment is therefore critical for maintaining immunocompetence: disruption is associated with reduced vaccine responses (directly shown in animal and human studies [141,142]), an increased infection risk, and enhanced chronic inflammation (as shown in animal studies) [137,138]. Indeed, epidemiological studies have reported associations between artificial light at night and elevated inflammatory markers such as C-reactive protein and IL-6 (reviewed in Fishbein et al. [135]). However, many of these analyses rely on satellite-derived exposure proxies and are limited in their ability to disentangle light exposure from co-occurring urban stressors, including noise, air pollution, and population density [143]. To assess light's effect on circadian regulation, the International Commission on Illumination (Commission Internationale de l'Éclairage – CIE) introduced the melanopic equivalent daylight illuminance (mel-EDI) metric [144]. Current guidelines recommend strong daytime exposure (≥250 lx mel-EDI at eye level) and very low levels in the evening (≤10 lx about 3 h before sleep, ≤1 lx during sleep). These thresholds help maintain circadian alignment, support alertness during the day, and minimize melatonin suppression at night [145].

Beyond circadian effects, visual enrichment is known to be associated with reduced stress and improved mood, attention, and performance on cognitively demanding tasks. The availability of weakly compelling visual features, such as natural views, plants, and curves, is associated with recovery of depleted cognitive resources and relaxation [146], as well as with the enhancement of working memory and attention. Accordingly, neuroimaging studies in humans show that visually rich and naturalistic settings suppress the activity of the amygdala (a brain area associated with adverse stress and fear) and enhance the connectivity of prefrontal brain areas involved in emotional regulation [147]. These changes are consistent with vagal activation and suppression of NF-κB–driven cytokine transcription via the cholinergic anti-inflammatory pathway, mediated by acetylcholine receptors on macrophages [148]. Notably, perceived control over visual conditions, such as the ability to adjust shading or lighting, has been shown to enhance satisfaction and productivity [149], potentially being able to reduce stress and amplify the benefits of visual enrichment [110].

Color variation has an influence as well: research in humans indicates that hot hues may raise excitement and energy, while cool colors may instate tranquility, though the subjective interpretation of color is conditional and may differ between cultures and individuals [150–155]. This underlines the importance of adapting design techniques to the specific individual's background. While direct evidence for colour-driven immune modulation is lacking, its known impact on emotional tone [156] provides an indirect pathway to neuroendocrine and immune effects [150]. From the salutogenic perspective, the visual bleakness of most modern interior environments, with white walls of mundane uniformity, artificial lighting, and orthogonal geometries, may be an insidious yet relentless sensory stressor. This visual deprivation in a monotonous environment may elicit cognitive fatigue, flattening of emotions, and even inflammatory responses, as already observed almost seventy years ago in aviators exposed to prolonged unchanged environments [157]. Accordingly, literature in visual alliesthesia [56,57,158] suggests that alternating visual conditions based on internal states (e.g., lights after sleepiness, natural forms after screen exposure, rhythms of daylight) might enhance pleasure and perceived comfort .

Overall, visual variability is biologically relevant and is associated with modulation of circadian rhythms, emotional tone, cognitive performance, and immune-related physiological processes. However, the direct link between visual variability in buildings and long-term neuroimmune or clinical health outcomes will benefit from further human experimental evidence, since most human studies assess short-term circadian, neuroendocrine, or psychophysiological markers (e.g., sleep timing, melatonin suppression, cortisol rhythms, autonomic balance), while immune biomarkers and disease endpoints are more commonly investigated in animal models or inferred indirectly through epidemiological associations, which cannot distinguish light effects from co-occurring urban stressors (see Q10 and Table 1 for further discussion). Nevertheless, salutogenic design must intentionally integrate visual variability in terms of natural and artificial light, palette, pattern, texture, and spatial movement, in order to foster health, well-being, and adaptive performance.

2.7. Question 7: how can soundscape variability promote health?

Traditionally, the acoustic quality of the built environment has been assessed based on sound pressure levels, assuming a close relationship between physical quantities (decibel-based metrics) and noise annoyance, with the ultimate goal of reducing acoustic stimuli, inherently regarded as noise [159]. Recently, these assumptions have been challenged within the framework of indoor soundscape approaches, which recognize that the soundscape is a perceptual and highly individual construct of a physical acoustic environment [29]. These approaches emphasize its strong contextual dependence and highlight the potential role of sound in shaping positively perceived spaces [160].

In the acoustic domain, much of the evidence linking sound exposure to immune-related outcomes derives from animal models and from human studies focusing on stress physiology rather than direct immune endpoints. The human perception of sound is closely associated with the activation of the autonomic nervous system, with unpredictable, repetitive, or very loud noise, especially mechanical noise, being associated with enhanced sympathetic nervous system activity, increased cortisol and catecholamines release, and increased heart rate and blood pressure: chronic exposure to stressful, noisy environments is associated with systemic inflammation and immunosuppression (reviewed in Evans [161]). Animal models show that chronic exposure to environmental or industrial noise provokes neuroinflammation, with increased IL-6 and neutrophil infiltration in the cochlea and inflammatory activation of the auditory cortex [162–164]. Conversely, as shown by several observations in humans, exposure to natural, and calming sounds has the potential to relieve stress and elicit parasympathetic activation, with overall benefits to recovery and immunocompetence [165].

The affective response to the soundscape can be explained in terms of two main dimensions that define a circumplex model: pleasantness (or comfort, in indoor residential settings) and eventfulness (or content) [32,166]. Temporal variability of the acoustic environment is generally associated with the eventfulness dimension, but a soundscape that is richer in events is not necessarily perceived more positively. While there is an established association in the literature between pleasantness and psychological well-being (WHO-5 index) [167,168], such a link does not appear to exist for eventfulness (or content); in fact, a negative relationship has been observed for males, i.e. more eventful soundscapes were associated with lower psychological well-being [168].

Spatial variability, on the other hand, seems to underlie the perception of calmness [169] and can be used as a design strategy [15]. Soundscape variability can be thus defined as fluctuations in acoustic conditions over time and space. Such variations can be experienced as dynamic and enlivening instead of distracting, depending on the activity at hand and type of source, among other factors. Natural soundscapes, like the rustle of leaves, birdsong (though not always) [170], or water movement, have proven to be highly effective in evoking positive affective experience and reducing physiological arousal that is caused by activation of the sympathetic system. Evolutionary psychology provides an explanation for this phenomenon: natural auditory signals have long been indicative of safety and availability of resources [165,171].

The availability of control over the environment and the specific context significantly influence the effect of sound and, as said for color, are conditional on the individual. Acoustic environments that are considered acceptable in one setting (i.e., music in a coffee shop) can be stressful in another one (i.e., a hospital). Individual perception of the source, noise sensitivity, and meaning of the sound can be more predictive of physiological response than the objective sound pressure levels (in decibels) of the sound [110]. This implies that health-promoting soundscapes are highly individual, culture-specific and dependent on the setting, and as such should be negotiated to address aspects of aural diversity [172].

The restorative value of variability in soundscapes is strengthened by studies showing that natural sound exposure increases cognition, reduces perceived pain, and facilitates emotional regulation. For instance, hospitalized patients who are treated with music or natural sounds (inherently variable stimuli) have reduced anxiety and improved recovery rates (reviewed in Ulrich et al., 2008 [146]). In urban environments, occasional natural soundscapes in conjunction with the ambient din, like fountains, wind chimes, or birdsong, might dull the physiological impacts of the city's background noise.

It is important to notice that human experimental evidence that directly links soundscape variability inside buildings to long-term neuroimmune outcomes is limited (please refer to Q10 for a more in-depth discussion of the quality of the available evidence). Most rigorous human work measures *short- to medium-term* physiological stress markers (heart rate, blood pressure, cortisol) or patient outcomes (sleep, length of stay), while immune biomarker data are more commonly reported in music-therapy or perioperative clinical settings [173–175]. The neuroimmune mechanisms through which soundscape variability could influence these parameters are described in Fig. 2. Overall, soundscape variability should currently be understood as a factor associated with the modulation of stress-related pathways that may indirectly influence immune regulation, rather than as a demonstrated causal driver of immune health in built environments. Accordingly, soundscape variability, if positively and appropriately experienced, can play a role in enhancing salutogenic design. Therefore, rather than a priori excluding acoustic stimuli, designers should endeavor to design acoustically rich and variable environments, tailored on occupants' preferences, that promote cognitive restoration, emotional well-being, and physiological recovery.

2.8. Question 8: what role does olfactory and gustatory variability play in promoting health?

Chemical senses (olfaction and taste) are closely associated with emotional processing, stress reaction, memory, and immune response. New evidence is building that the variability of olfaction and taste (i.e., the exposure to an array of odors and flavors over long periods) might be an important salutogenic factor, in that it can influence neuroendocrine responses and physiological adaptability. Accordingly, mechanistic support for olfactory-immune interactions is robust in animal models, though human evidence largely stems from small-scale experimental or quasi-experimental studies assessing acute immune markers. Smell and taste stimuli are unique in that they directly engage the brain's limbic regions, namely the amygdala and hippocampus. Accordingly, they automatically elicit autonomic and emotional reactions, including changes in respiration, heart rate, and cortisol levels, as observed in studies in humans and in animal models [176,177]. Delightful and familiar odors, for instance, alleviate anxiety and stress, while unpleasant or repetitive olfactory configurations have the potential to cause discomfort, disorientation, and inflammation [177].

Experimental animal studies provide mechanistic support for these effects. Specific odorants, such as plant-derived phytoncides and other volatile organic compounds, modulate immune activity by reducing pro-inflammatory cytokines and enhancing natural-killer-cell function. Conversely, olfactory deprivation in animal models has been shown to alter immune development and impair the maturation of immune-regulatory networks, indicating that continuous olfactory stimulation is essential for maintaining immune homeostasis [178].

One of the strongest lines of evidence comes from studies on the effects of "forest bathing" (Shinrin-yoku) in humans, a multidimensional intervention that combines olfactory exposure to phytoncides with visual, auditory, thermal, and tactile stimulation, as well as low-intensity physical activity. Within this complex exposure, inhalation of phytoncides, volatile organic molecules emitted by trees, has been demonstrated to be associated with increased NK-cell activity, enhancement of immune surveillance, and inhibition of inflammatory cytokine production [179,180]. All these effects persist several days after exposure, demonstrating the long-term immunoregulatory influence of natural odor stimuli.

Similarly, gustatory variability could have potential health implications, since individual differences in taste perception influence habitual dietary choices and are associated with variations in food intake and microbiota composition. Indeed, greater dietary variety, often linked to richer sensory experiences and nutrient-dense food choices, correlates with increased gut microbiota diversity, as seen in cross-sectional studies in humans [181,182]. Diet–microbiota interactions play a key role in human metabolic and immune outcomes, suggesting that nutrient-dense and diverse sensory intake can enhance metabolic function and influence immune competence [183]. Further, perception of the sense of taste is substantially dependent on olfactory input; over 80 % of the perception that is registered as the "flavour" is the result of the sense of smell [184].

From the psycho-neuro-immunological perspective, scent and flavor stimulations also have an impact on the HPA axis and potentially modulate cortisol release. Olfactory stimulation through scents such as citrus and lavender has been shown to influence the hypothalamic-pituitary-adrenal (HPA) axis and modulate stress hormone release. In humans, fragrance inhalation of citrus essential oils reduces plasma cortisol levels, and studies of lavender and other aromatic essential oils demonstrate sedative effects mediated through HPA axis interaction and lower circulating cortisol, often accompanied by reductions in subjective stress and anxiety, as reported in human clinical studies [185–187]. However, buildings that are overly deodorized and sterilized, and which provide poor olfactory input, might disrupt sensory integration and deprive the setting of the stimulus richness, which is physiologically essential. This aspect aligns with recent research on indoor smellscapes [30,33], which considers indoor air quality not merely in terms of pollutant concentrations and the pursuit of olfactory neutrality, but also in terms of the potential for odors to function as a deliberate design element. The gustatory contribution of architecture is certainly unconventional and challenging; however, as discussed by Spence [171], the materials and colors used in architectural design can evoke oral sensations, and the design of a space itself can influence the perceived taste of food.

Therefore, variations in smell, and even taste, may contribute to salutogenesis by decreasing stress, boosting the immune system, promoting dietary health, and sustaining cognitive performance. Nevertheless, while claims regarding the immune benefits of olfactory or gustatory variability in buildings should be interpreted as hypothesis-generating rather than conclusive (see also Q10 and Table 1), variations in smell, and even taste, may contribute to salutogenic processes primarily through stress modulation, dietary behaviour, and neuroendocrine pathways, with immune-related effects remaining indirect and context-dependent. For these reasons, they are underexploited sensory modalities that deserve attention in the design of salutogenic environments.

2.9. Question 9: how does tactile sensory variability impact health?

Touch is the earliest-developing and one of the most evolutionarily conserved senses. It is also crucial for facilitating social bonding and emotional development, and affects the immune system and physiological responses to stress. Tactile sensory variability refers to the dynamic range and diversity of touch-related sensory inputs that a person experiences over time and space. In other words, the term refers not only to a single texture, material or pressure, but also to how touch sensations change, fluctuate, or layer across an environment.

Touch-related information is processed by the somatosensory system, which is connected to the limbic areas of the brain responsible for emotions, motivation, and autonomic regulation. Studies in both animal models and humans suggest that tactile stimulation can modulate stress-related neuroendocrine responses, including reductions in cortisol and shifts toward parasympathetic activity. Accordingly, tactile experiences have the potential to alter physiological and emotional states. For example, C-tactile afferent fibers, a class of low-threshold mechanoreceptors in hairy skin that respond preferentially to gentle, slow touch, are associated with oxytocin release, reductions in cortisol, and increased parasympathetic activity in experimental settings. These responses engage neuroendocrine and autonomic pathways that are implicated in the regulation of inflammatory processes, thereby providing a plausible link between affective touch and immune-related outcomes, as shown by animal and human studies [188,189].

Accordingly, spaces that are abundant in tactile stimuli, such as organic textures including fabric, stone, wood, and vegetation, have been associated with increased perceptions of safety and comfort in a limited number of experimental studies involving human participants. In one recent experiment with human adults, exposure to such materials was associated with reduced sympathetic nervous system activity in indoor settings, alongside improvements in subjective well-being [190]. By contrast, another recent study involving human participants, though not focused exclusively on tactile input, reported that monotonous or impoverished sensory environments, including uniform and unchanging surface conditions, may negatively affect stress regulation and cognitive function [191].

The importance of tactile variability in health is further supported by studies of environmental enrichment in animal models. In particular, rats kept in environments enriched with a variety of textures showed increased neurogenesis, improved stress resilience, and immune activation, particularly in microglial and T-cell function [192,193]. These experimental outcomes are reminiscent of observations made in people receiving touch therapy or tactile stimulation (for example, a massage), which has been shown to increase vagal tone, lower cortisol levels, with downstream implications for inflammatory regulation, confirming that activation of parasympathetic pathways through touch can modulate immune-relevant stress responses [189,194–196]. Tactile interaction also fosters embodiment, a sense of connection between the self and the surrounding environment. In architectural spaces, tactile variation can encourage exploration, attention, and active engagement, rather than passive occupation. Such engagement is associated with increased perceived control, a key factor in salutogenesis and stress buffering [110]. Beyond tactile contact, proprioceptive stimulation, arising from body movement and physical activity, shares overlapping neuroendocrine pathways. Regular, varied exercise enhances immune surveillance and exerts strong anti-inflammatory effects by modulating cytokine balance and promoting parasympathetic recovery, as documented in recent reviews [197,198]. In addition, tactile indicators of temperature (e.g. cool stones or warm wood surfaces) support dynamic thermoregulation and enhance multisensory richness by promoting thermal alliesthesia, as indicated by a study involving human adults [199]. These minute but significant skin-environment interactions trigger thermoreceptors and affect autonomic function and comfort perception. Design strategies to enhance tactile variability include the integration of natural, uncoated materials, contrasting textures, variable surface temperatures, and opportunities for physical interaction (e.g., handrails, seating, flooring). Such approaches can be tailored to different populations, such as older adults, children, or neurodivergent individuals, who may benefit disproportionately from multisensory stimulation [112, 200–202].

In conclusion, while evidence linking tactile variability in architectural settings to long-term immune or health outcomes in humans remains indirect and largely extrapolated from experimental or therapeutic contexts (Q10 and Table 1 for further details), tactile sensory variability remains a potentially powerful but underutilized tool for enhancing health in the built environment via neuroendocrine, immunological, and emotional pathways, which actively contribute to physiological regulation and resilience.

2.10. Question 10: what is the agenda for future research and practice in the area of sensory variability in the built environment for health creation?

So far, this article has outlined the neuroimmune effects that environmental variability across the senses has on building occupants. Associations, mechanistic plausibility, and causal inference have been intentionally distinguished, reflecting the uneven maturity of the evidence base across sensory domains as qualitatively summarized in Table 1. Far from being a systematic review, the present synthesis aimed to suggest, based on the consulted literature on both animal and human studies, the relative robustness of findings across domains, highlighting key references. Specifically, the evidence appears: (1) strong for visual variability in circadian-light exposure (supported by both animal and human studies); (2) strong for thermal variability in animal studies, but moderate in humans; (3) moderate for tactile stimuli in both animal and human studies; (4) moderate (animal studies) to limited–moderate (human studies) for olfactory-gustatory variability; (5) limited–moderate (animal studies) to limited (human studies) for soundscape variability.

This synthesis can serve as a preliminary guide for future research, pointing to the need to strengthen evidence in less explored areas (e.g., neuroimmune effects of soundscape, tactile, and smellscape variation). Future studies, first in animals and then in humans, should not focus merely on the presence of sensory stimuli, but rather on their variability. Defining the very concept of variability should therefore be the first step: with which frequency should a stimulus vary, temporally or spatially? What degree of change is meaningful enough to be physiologically or psychologically perceptible? What is the maximum range of variation beyond which stimulation becomes harmful? What are the domain-specific parameters needed to *measure* variability? To what extent should variability also be rhythmic? Only then can links with immune system responses be meaningfully established.

In the thermal domain, the literature has already examined human perceptual responses to step changes, gradual drifts, and cyclic variations in air temperature, making the definition of variability clearer [203–210]. Studies also showed that excursions outside of the neutral zone (variation rates of 2.28 °C/h staying within the range of 17–25 °C) can be applied in practice without considerably affecting the thermal comfort, improving thermoregulatory capability, and having a positive role on CO_2 footprint and buildings' resilience to climate change [211, 212], as well as supporting occupant resilience and thermal enjoyment [23]. Nevertheless, the research agenda on dynamic thermal perception is still far from being completed [213]. Similarly, in the visual domain, studies have examined the effects of dynamic lighting and view quality on circadian regulation, emotional tone, and cognitive performance, showing that variations in intensity, spectrum, and direction, can support health without compromising, and even enhancing, overall comfort [28,118,133,214–220]. Despite this, uncertainty remains, for instance in the individual differences in terms of visual and non-visual light effects [221,222], and the evidence for non-circadian visual features (such as views, spatial complexity, or color), which are primarily linked to stress reduction rather than immune endpoints.

The acoustic domain presents challenges, since most sounds and noises inherently fluctuate in both time and frequency, yet they are not all beneficial. Further research will be required to determine what type of variability is immunologically meaningful for soundscapes, and how to characterise it, also based on the existing concepts of musical rhythm, soundscape complexity [223], or ecoacoustic indices that describe patterns in acoustic environments (e.g., Acoustic Complexity Index [224], Acoustic Diversity Index [225], etc.). Moreover, future research should investigate the effects of sensory variation across different target groups, such as neurodivergent individuals, children, older adults, or other vulnerable groups, who may benefit differently from multisensory dynamic stimulation, while also being more vulnerable to sensory overload [112,113,222,226]. As highlighted in Q5–Q9, individual differences influence IEQ perception and may also affect physiological and psychological responses, and thus salutogenic design solutions.

Overall, data and considerations described here amount to a call for studies, first on animals and later on humans, to strengthen the available evidence. Laboratory studies are useful for isolating single variables and observing acute effects on test participants. Studies conducted in real buildings (e.g., randomized trials on target buildings such as nursing homes) can help observe medium- to long-term effects in more ecologically relevant settings, while also enabling causal inferences. These can be complemented by surveys and interviews with building occupants to further explore links between their health status, frequency of illness, and the design features of their residential or workplace environments. Finally, epidemiological observational studies can contribute by gathering evidence from large-scale datasets, such as housing and health registers, to investigate correlations between specific health conditions and environmental characteristics [227], although, in this case, the challenge of isolating the effects of individual variables must be taken into account. To advance this research agenda, as evident from the present discussion, future studies should foster collaborations between researchers in architecture and indoor environmental quality and experts in clinical medicine, psychology, neuroscience, immunology, biology, and public health, among others.

From a design-oriented perspective, many traditional architectural practices inherently embed environmental variability, as already noted. Examples include natural ventilation and daylighting, where thermal and visual conditions vary with the day–night and seasonal cycles, and where indoor environments remain connected to outdoor soundscapes, smells and views [26,42]. Nevertheless, these connections must be carefully managed to avoid exposure to harmful stimuli such as traffic noise and air pollution. Other design strategies rely on the juxtaposition of materials, and textures, the shaping of architectural forms and volumes to create movement and variation [228], or the use of color in interior design to enhance dynamism, depth and fluctuation. Over time, more advanced technologies have enhanced these traditional approaches, complementing or supplementing controlled variability; for instance, building management systems regulating HVAC with adaptive algorithms, biodynamic and daylight mimicking lighting, or active soundscaping systems with spatial and temporal modulation.

Finally, it is interesting to notice that the concept of sensory variation aligns with recent work on the "probiotic home" [229], calling for the deliberate reintroduction of beneficial microbes into the built environment to replace sterility with microbiological diversity. Even if such studies would benefit from further research and scientific evidence, both approaches share a common rationale: to reproduce, within artificial spaces, aspects of the natural complexity that shaped human evolution. Just as the absence of microbial diversity impoverishes immune education, the loss of sensory variability diminishes neuro-immune adaptability. Interestingly, many sensory variability practices are still largely justified by evidence of their aesthetic or affective benefits. Only partially does research, as highlighted above, substantiate a clear link with occupant health in multisensory dynamic environments. We believe it is time to propose the development and implementation of building design strategies and technologies that enable the conscious orchestration of dynamic environmental patterns in architecture, both spatial and temporal, supported by growing evidence of their salutogenic potential.

3. Conclusion

This paper brings together an interdisciplinary team of researchers from architecture, indoor environmental quality, neuroscience, and immunology to define the concept of salutogenesis in building design. We propose that health promotion in architecture can be achieved through dynamic engagement with stressors, embracing the concept of eustress (a positive form of stress that can enhance performance, motivation and well-being). Applying Antonovsky's model to the built environment, we identify sensory variability (across thermal, visual, acoustic, olfactory, gustatory, and tactile domains) as one of the key mechanisms to train the body and sustain immune balance, so enabling movement toward the health end of the healthy/dis-ease continuum. Drawing on selected animal and human studies, we discuss how dynamic environments stimulate neuroimmune responses via the Hypothalamic–Pituitary–Adrenal (HPA) axis and autonomic nervous system, supporting resilience and promoting health.

Evidence for sensory variability is uneven across domains: visual and thermal variability show stronger support, especially in regulating circadian rhythms, stress, metabolic, cardiovascular activities and immune responses, while tactile stimulation also demonstrates moderate anti-inflammatory and immunological benefits. In contrast, soundscape and olfactory variability show more limited support in humans, with potential benefits influenced by individual and cultural factors.

Based on these results, we propose a research agenda moving beyond examining the mere presence of sensory stimuli and instead focusing on their variability, such as temporal rhythms, spatial dynamics, and domain-specific parameters. Research should also strengthen the evidence base in underexplored domains (e.g., soundscape, olfactory–gustatory, tactile), include diverse populations, and promote interdisciplinary collaboration among architects, environmental scientists, psychologists, immunologists, neuroscientists, clinicians, and public health experts, among others.

From a design perspective, we advocate for salutogenic interventions that embrace dynamic sensory stimulation, e.g. through natural ventilation and daylighting, material and texture variation, adaptive lighting and soundscaping, as well as allowing spatial and temporal variations of temperature. This fosters a movement beyond the mere marketing-driven justification of salutogenic design, toward evidence-based health outcomes. This approach complements, rather than replaces, design for well-being, as sensory variability may also enhance pleasure and alliesthesia, while, at the same time, targeting long-term health outcomes.

Ultimately, this paper advocates a shift in design thought—from static comfort toward dynamic health creation—achieved through the deliberate orchestration of environmental diversity as a rhythmic, multisensory experience, thus bringing Goethe's dictum, "Architecture is frozen music," to life.

CRediT authorship contribution statement

Rossano Albatici: Writing – review & editing, Writing – original draft, Supervision, Formal analysis, Conceptualization. **Yuri Bozzi:** Writing – review & editing, Writing – original draft, Formal analysis, Conceptualization. **Massimo Pizzato:** Writing – review & editing, Writing – original draft, Visualization, Formal analysis, Conceptualization. **Simone Torresin:** Writing – review & editing, Writing – original draft, Supervision, Formal analysis, Conceptualization. **Luca Zaniboni:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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