Sensory perception of humidity in the built environment for wellness: a scoping review

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Water vapour in the air is an essential element that directly affects all animate and inanimate constituents of the planet. It is a fundamental constituent in all interactions that characterize life and planetary systems. Water vapour in the air is distinctly associated with the functioning of the human sense organs. All five senses, i.e. smell, touch, sight, sound and taste respond to water vapour in the air. The sensory mechanisms determine a human being's physiological and psychological balance, which is the foundation of wellness, relevant on a planetary scale. However, the sensory mechanisms associated with water vapour in the built environment have not been discerned holistically, particularly its role in human wellness. The present article reviews sensory perceptions and responses attributed to humidity/water vapour in the built environment and examines its role in promoting human wellness, drawing insights from diverse interdisciplinary disciplines.

Keywords: Comfort, health, humidity, indoor environmental quality, sensory perceptions, wellness.

IN all its forms (ice, water and water vapour), water is fundamental to life. Seventy per cent of a human body weight is water, and a meagre deviation of 2% can be fatal. The human body thrives on maintaining equilibrium with its surroundings to ensure this water balance.

Balancing the physical self and the external environment is crucial to facilitate wellness. The sensory perceptions (associated with the mind) and associated responses (associated with physiological reflexes) are responsible for this balance (Figure 1). The sensory response is a voluntary and/or involuntary response to environmental stimuli, with the mind/brain being the command, interpretation, and decision centre. In humans, this is subjective to stimuli and sensitivity of different sense organs and the state of mind. It is affected by personal factors, personality/attitudes, past experiences, sensitivity and expectations.

A good example is acclimatization to different climatic conditions[1]. The expectations of an individual for a summer thermal environment can be as hot as 40°C (climatological mean maximum temperature of hottest months) in Jaipur, Rajasthan (India); however, the same in Darjeeling, West Bengal (India) could be 20°C only[2]. Therefore, a person from Jaipur may not find it warm in Darjeeling.

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The five senses, i.e. sight, touch, smell, taste and sound, allow humans to build a relationship with their surroundings to facilitate the co-existence and evolution of both on earth through various physiological mechanisms. Though the organs associated with the senses, i.e. eyes, skin, nose, tongue and ears, are distinct, the sensory perceptions may be intricately connected depending on varying neuromotor coordination in different individuals[3,4]. For example, the aroma (smell) and texture (sight) could stimulate taste perception while brewing a coffee. The sound of coffee grinding or brewing could also stimulate the sense of smell and taste. However, water vapour in the air can influence distinct physiological mechanisms related to each of the senses and can still be understood concerning the distinct senses.

Human eyes are always moist; dryness can cause discomfort and illness and affect normal vision[5]. The hydration level of the skin influences the sense of touch. It facilitates heat loss/gain, ensuring thermoregulation and comfort. Water vapour in the air is a carrier of smell itself; also, the speed at which sound travels is influenced by it. Salivation results from the perception of taste and aids digestion[6]. Therefore, water vapour-associated mechanisms contribute to the functioning of the human body and comfort, affecting health.

Objectives and scope

This article explores each sensory mechanism associated with water vapour in the air that constantly surrounds the human body. The following are the objectives of the article: (i) Examining the association of water vapour in the air with the human senses. (ii) Mapping parameters influencing sensory response to varying humidity in healthy built environment designs. (iii) To identify interdisciplinary research challenges that need addressing in support of wellness.

Methodology

Studies addressing objectives 1 and 2, as mentioned earlier were selected. Keywords ('moisture' or 'humidity') and ('sensory perception or 'smell' or 'sight' or 'touch' or 'sound' or 'taste') were used to collect articles from Web of Science, Scopus and PubMed and PsychNET Journal

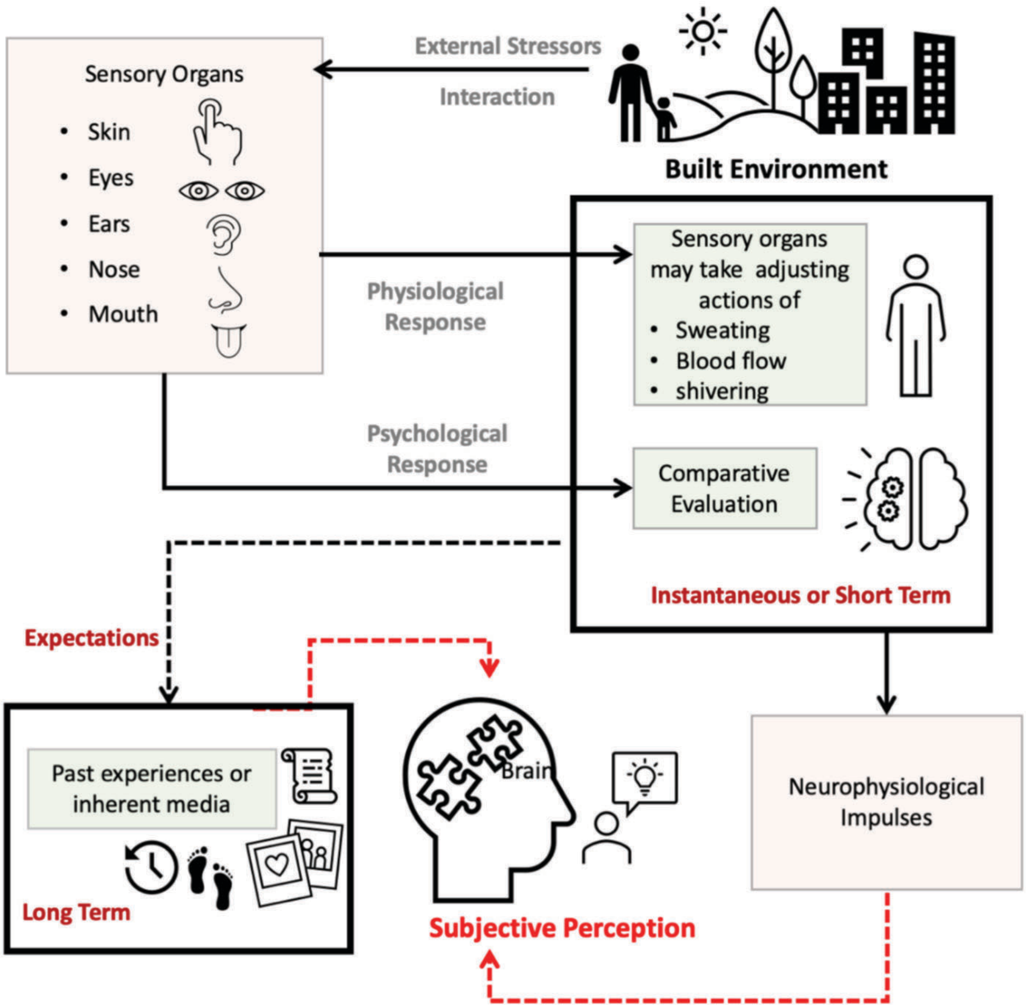

Figure 1. Human sensory perception and response mechanism (adapted and modified from ref. 45).

articles written in English. The keyword search resulted in 7872 articles. One hundred and sixty five articles were selected based on title screening and deletion of duplicates. Forty eight were further selected with abstract screening. Twenty nine articles, deemed eligible for this review, were selected for inclusion and detailed analysis (Table 1). Additional articles were included to build on the insights from these 29 articles. The manuscript was structured to present a broader understanding of the current knowledge about how moisture in the air interacts with the human senses. Hence, the focus on the quantitative results from detailed studies was limited. This methodology was in line with the preferred reporting items for systematic reviews and meta-analyses (PRISMA) guidelines for Scoping Reviews[7].

Limitations

The discussion in the article is limited to the association of water vapour with each of the human senses distinctly. The interaction and dependencies between the senses are far more complex. They are mentioned but have not been explored in detail in this article.

Sensory perception of humidity

Humidity and smell

The smell is the foremost sensory perception, fundamentally associated with breathing and establishing primal bonds. An infant identifies its mother after birth through smell[8]. In animals, smell acts as a territorial marker and a medium of physiological communication, influences courtship and mating, and dominates behaviour and stress.

Smell is associated with the nose as a sensory organ. The perception of smell is associated with humidity levels in the air as it is the odour carrier. Inhaling (water) vapour in air through the nostrils with other substances trapped (determinants of smell) is the basis of smell perception[9]. Modern-day applications of diffusers use liquid water medium for fragrance and disinfection. Humans identify

Table 1. Analysis of articles retrieved from systematic search

Source	Results demonstrated	Remarks/salient takeaways
Sound		
Tronchin[33] (2021, Italy) Lab-scale experimental study	• Strength, clarity, and reverberation time of the sound significantly associated with temperature (T) and relative humidity (RH). Reverberation time increases at high frequencies with increase in T and RH. • The impact of T and RH is dominant at low air velocities.	• The propagation of sound depends upon the medium. As the density of air significantly changes with the change in absolute humidity, absolute humidity could be explored to examine sound quality. • Conducting similar experiments with a broader range of T and RH (or absolute humidity) is needed for varying building typologies and climates.
Zhou *et al.*[34] (2014, China) On-field measurement + subjective questionnaire survey	• People who are comfortable with their thermal environment (T, RH, wind velocity) and cultural environment and public spaces (public sanitation, amenities, landscaping and green areas, vitality) tend to show acceptability towards their acoustic environments. • Age, occupation and exposure affect acoustic satisfaction.	• Thermal environment as influenced by T and RH have a great bearing on acoustic comfort/ satisfaction. • Given the indirect impact of perceived thermal comfort on acoustic comfort, it is essential to establish benchmarking limits for sound pressure levels vis-à-vis varying T and RH.
Meng *et al.*[35] (2013, China) On-field measurement + subjective questionnaire survey	• Subjective loudness was higher in street type shopping places than in square type shopping places. • Both subjective loudness and acoustic comfort are influenced by RH. • The results suggest that in areas of relatively low humidity, subjective humidity is higher as humidity increases. Also, subjective loudness is lowered with increase in humidities in areas with relatively higher humidity. However, the difference in the mean RH between the areas of relatively high and low humidity is only 8%.	• Perception of sound quality (sound loudness) varies with RH. • The present study needs to be extended to examine a higher variation in RH vis-à-vis subjective perceived loudness to comment on its validity in low and high humidity conditions.
Harris[31] (1966, USA) Lab-scale experimental study	• Sound intensity varies with RH. • The attenuation may increase and then decrease to a constant value as we move from low to high humidity conditions. • Propagation of sound is higher in low humidity environments. • The magnitude of attenuation coefficient increases as the sound frequency increases.	• Sound attenuation and propagation vary with environmental parameters and sound characteristics, essential to examine in detail for optimum acoustic comfort.
Morfey *et al.*[32] (1980, UK) Computational study	• The results demonstrated were close to values reported by Harris *et al.*[31]; however the results could not explain disparencies at low humidity levels.	• Sound velocity in air can be calculated using this approach at RH > 20%. • This computational approach can be helpful in acoustic design as it does not require sophisticated experimental apparatus.
Taste		
Spence[60] (2017, UK) Review	• Humidity is directly associated with the partial pressure of the air. • At high altitudes, perception of bitterness, sweetness and saltiness decreases. • As a result, Asian spicy food is found tastier, poultry/meat is found bland, and fruit juices taste bitter.	• Decrease in humidity may be associated with reduced sensitivity to certain kinds of tastes. • Food habits directly impact health, and food preference is highly dependent on taste. • The applicability of this result at ground level with varying humidity levels needs further investigation.
Smell		
Sani *et al.*[18] (2022, Japan) On-field measurement + subjective questionnaire survey	• The study establishes through empirical relation, that mould is directly associated with high humidity. • Very high humidity leading to moulds can cause respiratory ailments.	• Building envelop design should ensure mould free indoor spaces.
Drews *et al.*[11] (2021, Germany) Experimental study in hypobaric climate chamber	• Healthy subjects with good olfactory response were not significantly affected for their smell perception in varying T/RH condition for 'rose-like' smell.	• Smell perception of people with varying olfactory responses need to be understood given its importance in built environment and comfort.

(*Contd*)

Table 1. (*Contd*)

Source	Results demonstrated	Remarks/salient takeaways
Grabe *et al.*[9] (2018, Germany) Review	• The chemical pollutants in the air and their concentration decide their smell perception (aromatics are heavy compounds that have intense odour).	• Even though certain chemicals (low molecular mass) may be present in the environment, their smell may not be perceived. The long-term impact on such chemicals on health is crucial to examine for healthy built environment design.
Lorentzen *et al.*[19] (2016, Sweden) Experimental data synthesis	• Chloroanisole induced malodour in buildings is associated with health vulnerabilities. • Chloroanisoles may be associated with symptoms and health effects associated with sick-building syndrome.	• Even though toxicological evaluation suggests no major risk to health, the symptoms like headache, allergies, etc. are evident and can result in lack of productivity in day-to-day activities.
Altundag *et al.*[14] (2014, Turkey) Experimental study at high altitude	• Olfactory functions decrease at higher altitude. It can be related to higher altitude-induced lower T, pressure and humidity. • This study focused on felt-tip pen odour sensitivity.	• Design for high-altitude buildings should consider lower sensitivity to certain smells. • It is crucial to examine sensitivity of various smells with varying T and RH.
Kuehn *et al.*[12] (2008, Germany) Experimental study climate chamber	• The olfactory response was found lower in hypobaric (low humidity) conditions when compared to hyperbaric (high humidity) conditions. • Butanol odour olfactory thresholds are impaired in low humidity conditions. • Highest sample size amongst similar studies.	• Design for high-altitude buildings should consider lower sensitivity to certain smells. • It is crucial to examine sensitivity of various smells with varying T and RH.
Philpott *et al.*[13] (2004, UK) Experimental study in a room	• Olfactory threshold/response was found independent of environmental parameters. • Rose oil olfactory thresholds were not found to be associated with environmental parameters.	• Smell is not associated with indoor environmental parameters and may not be examined for built-environment design.
Wargocki *et al.*[28] (2001, Denmark) Review/comment	• The paper presents a methodology to determine acceptability threshold with simultaneous measurements of psychophysical data, odour intensity, ventilation and varying subjective acceptability. • Different odorants need to be examined with varying environmental conditions to prepare an inventory of odour intensity and corresponding threshold of acceptability.	• The understanding of acceptability limits for varying odorants will help in designing healthy and conducive spaces.
Touch		
Uemae *et al.*[39] (2022, Japan) Experimental study in climate chamber	• Occupants report feeling muggy, sweaty, stifling and humid at high T and RH. • Perception is dependent upon relative evaluations and neutral comfort state. As the thermal environment moves from neutral, the evaluation shifts in a negative direction, i.e. sense of discomfort, and when it approaches a neutral environment, the evaluation is positive, i.e. sense of comfort. • Responses depend on gender, activity levels and thermal properties of clothing (breathability, thermal conductivity, heat retention, moisture absorption/desorption, etc.).	• All individuals do not have neutral comfort state; hence it is crucial to examine it for efficient design for comfort.
Xie *et al.*[40] (2021, China) On-field measurement + subjective questionnaire survey	• The high humidity is associated with low perceived air quality and negative thermal comfort. • Sweat due to high humidity has been associated with bad odour. • RH is found in best association with CO_2.	• High humidity must be avoided in places where occupants are involved in strenuous activities. • Sports environment should be designed ensuring optimum thermal comfort.
Cymes *et al.*[17] (2021, Poland) Retrospective cohort data study	• Heat-related fainting increases with external T, more so with increase in humidity. • Universal thermal climate index (UTCI) (indicator based on heat balance of the body) was found as an apt indicator to predict fainting.	• High T and humidity (thereby high UTCI) in the environment can restrict heat loss and result in excessive heating up of body, resulting fainting/collapse. • UTCI predictions in cities can lead to predictions of possible risks of fainting/collapse.

(*Contd*)

Table 1. (*Contd*)

Source	Results demonstrated	Remarks/salient takeaways
Xie *et al.*[40] (2021, China) On-field measurement + subjective questionnaire survey	• Coal-fired stoves for indoor heating can deteriorate living environment significantly increasing CO_2 and particulate matter levels beyond healthy limits. • Rural residents show higher adaptation to T and humidity.	• Adaptation of subjects living in rural areas is different than subjects living in urban areas. • Living condition (fuel use) have a bearing on indoor air quality (IAQ).
Merrick *et al.*[42] (2019, UK) Review/comment	• Wettedness perception is extremely important for object perception. • It provides cues for possible health problems, for instance, discomfort to child with itchy skin to avoid dermatitis.	• Biometeorological factors may alter wetness perception, thereby affecting perception of objects.
Liao *et al.*[43] (2018, China, Japan) Experimental study in climate chamber	• Touch receptor thresholds can be affected by acclimatization to T and RH for smoothness perception. • RH was found to have a negative impact on warmth perception of fabrics. • A negative correlation between warmth and adapted RH may be due to the good heat transition properties of water and water vapour.	• Clothing in conjunction with environmental parameters can impact thermal response. • Thermal comfort studies must consider smoothness of fabric as an indicator impacting thermal sensation.
Ackerley *et al.*[44] (2014, Sweden) Experimental study	• Moisture is associated with a feel of cold, reduction in friction and thermal smoothness. • Even though more moisture may result in the ease of friction, enhancing smoothness, it may be a determinant of warmth when at the same humidity and T are higher.	• Design for thermal comfort must be done hand-in-hand with clothing and fabric type used by occupants.
Filingeri *et al.*[48] (2013, UK) Experimental study	• The perception is a result of complex interaction between physiological and psychological mechanisms. • The cooling rate of the skin is important to evoke the sense of wetness (This could be related to human beings not perceiving insensible perspiration). • Cold dry is difficult to perceive and is often perceived as cold-wet. • This study reported that cold-wet sensation was perceived at a cooling rate of 0.14°–0.41°C/s.	• Perception of wetness may be compromised at lower T due to high cooling rate of the skin.
Li[88] (2005, Hong Kong) Experimental study	• Highly hygroscopic fabrics like wool offer more effective buffer to the body against sudden T and humidity variations than acrylic. • Dampness rating is negatively correlated to warmth rating and skin T. • Comfort rating is positively associated to warmth rating and negatively associated to dampness rating. • Perception of warmth is found directly associated to skin T.	• Dampness sensation counters warmth sensation in human subjects.
Dent[54] (2001, USA) Computational study	• This article is about modelling the buffering (cooling) effect of fabrics related to after-exercise chills. • The paper discusses the mechanisms through which fabrics act as barriers between the environment and human skin. • Denser, hydrophilic fabric offers higher buffering to T and humidity, and it can be explained using Henry's theory.	• Hydrophilic, dense fabrics provide more buffer to sudden variations in T and RH.
Li *et al.*[53] (1995, Australia) Experimental + computational study	• Fibre hygroscopicity was identified as a key parameter determining subjective dampness perception. • The T drop that occurs locally on the skin due to the sweat is responsible for cooling-effect caused by fabric. Perceived dampness decreases with increased hygroscopicity of the fabric. • Wool caused lesser perception of dampness when compared to polyester as it was able to retain more moisture for a longer period. It implies that the relative skin T drop in the case of wool is much higher than that of polyester.	• Hygroscopicity of clothing material is important for subjective perception of dampness.

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Table 1. (*Contd*)

Source	Results demonstrated	Remarks/salient takeaways
Li *et al.*[52] (1993, Australia) Experimental + computational study	• The T increase of the skin in contact with wool is slower compared to polyester. This could be attributed to the hygroscopicity of wool. • Wool fabric absorbs more water from the skin and desorbs when it comes in contact with the skin.	• Coolness to touch is observed more in wool than in polyester due to its high hygroscopicity.
Sight/multi-sensory		
Henshaw *et al.*[15] (2015, UK) Interviews	• This article explains the multi-sensory perception of indoor thermal environments of the elderly and emphasizes on sensory experience being an important determinant of cognition. • Moisture is associated with unwanted odour, and impacts the freshness of air.	• Moisture in conjunction with less ventilations impacts olfactory comfort and thermal comfort. • Sight of dampness of moulds can also trigger discomfort.
Sun *et al.*[28] (2007, China) On-field measurement + self-administrated questionnaire survey + building inspection	• The first presence of dampness/high moisture in buildings is reported as foul smell. • The sensation of dryness and wetness is temporary (or instantaneous and may not be reflected by daily/monthly average RH values), which a human being remembers, and it reflects in the responses of the questionnaire survey. • The association between dorm characteristics and health symptoms found in the study was poor.	• Visible dampness may be perceived detrimental and may trigger symptoms causing discomfort. • However, its association with health symptoms does not stand established yet.
Ncube *et al.*[63] (2012, UK) On-field measurement + subjective questionnaire survey	• The paper indirectly incorporates the impact of sensory perceptions (thermal comfort, perceived indoor air quality, acoustic comfort, indoor environmental quality (IEQ)) to demonstrate an integrated IEQ framework. • Presently the case of UK has been demonstrated, an empirical relation has been produced based on-field measurements and corresponding subjective comfort responses.	• This could be a good approach to operationalize implementing IEQ-based design. There is scope for detailing in each sub-segment of the framework. • Designing indoor healthy spaces needs to be looked at holistically, rather than focusing on thermal comfort alone.

smells due to the olfactory receptors in the nasal cavity, which detect the presence of specific chemical substances to signal the brain for its recognition. The intensity of smell also perceived depends upon the amount of diffusion of the chemical odorant in the air, for which moisture content of air plays a vital role[10]. This is attributed to the aroma of hot food spreading faster than relatively cold food. Studies suggest the relevance of odorant with the physical state in which it exists. The phase responsible for the perceived odour is the gaseous phase of the substance and depends upon its specific weight. 'To produce the sensation of smell, a substance must have a molecular weight at least fifteen times that of hydrogen.'[10] As we move above in the elemental series of carbon compounds, with an increase in specific gravity, the odour intensity increases. The heavier the substance compared to hydrogen, the higher the intensity of the odorant it is considered to be[9]. Given this context, humans are surrounded by complex chemicals all the time. The building materials, furniture, furnishing and lifestyle products comprise complex chemical constituents. These chemical constituents, in conjunction with environmental parameters (pressure, temperature, humidity, air movement/ventilation), are responsible for the perception of smell. However, experiments conducted to examine smell perception in human subjects have not revealed consistent results. Experiments conducted in controlled environments[11–13] examined different odorants and revealed mixed results. Drews *et al.*[11] (50 subjects) found negligible impact on humidity on smell perception of a rose-like odorant, whereas Kuehn *et al.*[12] (75 subjects) showed that sensitivity to butanol smell is impaired at low humidity. Philpott *et al.*[13] (10 subjects) found no impact of environmental parameters for rose oil smell. An experiment conducted at high altitude setting[14] (low vapour pressure, temperature and absolute humidity) concluded that olfactory response to felt-tip pen odour decreased. It is crucial to examine the sensitivity of various smells with varying indoor environmental parameters.

The smell of 'fresh' air rejuvenates the mind, uplifting an individual's mood[15]. Freshness in the air can be naturally induced through moisture (contributed through vegetation and/or water fountains or streams), stimulating the primal physiological response and activating the brain's 'feel good' centre. This is used in therapeutic aroma therapies to cure psychological disorders[16]. Moisture is known to aggravate the effect of odorants in the absence of ventilation and induce a feeling of 'lack of freshness'[15,17]. Moulds caused by high humidity in the absence of ventilation in buildings were strongly found to cause respiratory difficulties[15,17,18]. Chemical and biological interaction with indoor moisture and moulds was examined[19] using data from 499 Swedish buildings. The study concluded that chloroanisol-induced malodour in buildings is associated with health vulnerabilities. Chloroanisols may also be associated with symptoms and health effects associated with sick-building syndrome. Even though toxicological evaluation suggests no significant risk to health, however, symptoms like headache, allergies, etc. are evident and can result in a lack of productivity in day-to-day activities.

The importance of smell for comfort and indoor air quality (IAQ) is imperative[20–22], but its systemic role can vary. Room fresheners, perfumes, etc. are often used voluntarily for freshness and comfort, but the effects are short-lived and counterintuitive. The smell of volatile organic compounds (VOCs), found carcinogenic and harmful in recent studies, emitted from synthetic furniture, flooring, paints, etc. is part of the modern lifestyle. Short-term effects of constituent chemical exposure are often manifested by non-olfactory symptoms like watery eyes, headache, nausea, allergies, etc. Long-term is harmful to human health[23] and may adversely influence olfactory responses[22], cognitive performance, lack of productivity, and stress subsequently[24–27]. However, the interactions of these common chemicals of concern, like VOCs, endocrine disrupting chemicals (EDCs), etc. with indoor humidity and temperature are not very clear even though the harmful effects on humans remain very much established.

Better indoor air quality in terms of indoor humidity is characterized by its impacts on indoor thermal, skin-related, and respiratory comfort. The smell is closely associated with the inhalation of moist air and respiratory comforts. Wargocki *et al.*[28] presented a methodology to evaluate the threshold for odour acceptability for conducive indoor environments. However, studies examining the acceptability threshold of common smells are limited. Respiration occurs in the human lungs at 37°C saturated air. The heat and moisture exchange in the human respiratory tract conditions the indoor air in this state. This could be a reason for the prevalence of respiratory difficulties, asthma, etc. in cold and dry indoor environments. Indoor humidity, therefore, is essential for optimum indoor air quality, determining comfort and productivity. Ventilation and optimum moisture recommendations for healthy indoor environments remain inconsistent and ignored simultaneously. The smell, as affected by indoor humidity levels and the use of natural and/or synthetic odorants hand in hand, needs scrutiny in the context of wellness in living environments.

Humidity and sound

Sound is closely related to the moisture levels in the atmospheric air. The velocity of the sound increases with the rise of moisture in the air[29]. At the same time, with the rise in atmospheric moisture, there is a better possibility of sound absorption[30]. Studies suggested that sound intensity varies with relative humidity[31,32]. The attenuation may increase and then decrease to a constant value as we move from low to high humidity conditions, even when the velocity is higher. Propagation of sound (intensity) is higher in low humidity environments. The magnitude of attenuation coefficient increases as the sound frequency increases. Another study[33] conducted to examine variations in acoustic parameters (strength, clarity, definition, reverberation time, early decay time, inter aural cross-correlation, lateral efficiency, lateral fraction), with varying thermo-hygrometric parameters (temperature, relative humidity, air velocity) concluded that strength, clarity and reverberation time of the sound significantly associated with temperature and relative humidity. Reverberation time increases at high frequencies with an increase in temperature and relative humidity. Also, under low air velocity conditions (ventilation system turned-off), the acoustic parameters changed significantly, indicating the impact of temperature and relative humidity being dominant at low air velocities.

Noise triggers discomfort, leading to physiological changes like a rise in body temperature. The noise from outdoor traffic, an instrument, etc. can cause a loss of concentration and change thermal comfort levels. Studies[34,35] found an association between perceived acoustic comfort and humidity. Zhou *et al*.[34] found that acoustic comfort is directly associated with subjective evaluation of the thermal environment (temperature, relative humidity, wind velocity), cultural environment and public spaces (public sanitation, amenities, landscaping and green areas, vitality). People who are comfortable with their thermal environment tend to show acceptability towards their acoustic environments depending on personal factors like age, occupation and duration of exposure and are also responsible for acoustic satisfaction. Another similar study by Meng *et al.*[35] found associations of humidity with acoustic satisfaction unclear. Also, the range of variation in relative humidity in these studies was very narrow, and it needs more elaborate investigation.

Building acoustics is an important design parameter. The principles of sound reflection, transmission and absorption are widely used for acoustic designs for sound attenuation and amplifications at theatres and auditoriums. Material selection based on their acoustic properties is also essential to consider in the process.

Sound transmission and its relation with air density (related to humidity) have been studied extensively in the literature. However, its application for acoustic design in different building typologies/materials must be explored. Humidity variations attributed to different materials and their corresponding acoustic response would aid in improving the spatial quality of specific spaces like classrooms, auditoriums, etc. Certain hygroscopic materials have high sound absorption capacity; however, variation in acoustic performance with changes in moisture content in building materials has not been adequately investigated. It could open up novel research alongside moisture buffering studies impacting IAQ.

Humidity and touch

Touch stimuli are vital for the recognition of the physical attributes of an object (texture, temperature, etc.). Human skin is constantly exposed to water vapour from the air and responds to tactile stimuli. The sense of touch/ perception of texture requires the fingertips to be neither too wet nor too dry. The perception of humidity by the human body leads to an involuntary response to attain physiological equilibrium, determined by thermoregulation. Perspiration or heat and moisture exchanges occur in the body appropriately, ensuring thermal balance between the human body (through the skin) and the surrounding air to maintain a stable core body temperature. The ease of perspiration ensures better thermoregulation, contributing to thermal comfort and directly impacting productivity and health. A study[36] explained that the rising temperatures globally have led to the wet bulb temperature exceeding human skin temperature (35°C) at several locations. Such conditions can inhibit heat loss from the body through perspiration, causing morbid thermal retention, stroke and fainting[37], which could be fatal. A similar situation can be observed in air-conditioned environments where perspiration is restricted; the frequent urge for urination to expel water in the body can be observed[38]. Therefore, the autonomous retention and expulsion of water from the human body are, closely linked to ambient air temperature and humidity conditions. Features like fountains and small pools are often used in hot climates as passive design elements for cooling and humidification, ensuring thermal comfort.

Thermal comfort studies report that increased humidity aggravates discomfort at the same temperature. Low humidity levels promote higher evaporative losses from the skin; high humidity levels restrict it due to the inability of air to hold more water vapour. As heat loss through perspiration is restricted in high-humidity environments, it is often manifested through a higher thermal sensation vote[39–44]. The human body's thermal equilibrium is the basis of thermal comfort indices. Occupants subjected to controlled environments were interviewed for their thermal sensation votes to examine the comfort perception attributed to heat and water vapour loss/gain. Humidity in the air is perceived only when the difference in humidity levels in the air and human skin is significant enough to cause a physiological change – for example, dry skin and lips, thirst, sweating, irritation, cough, etc. At conditions below 23°C, 50% relative humidity, the change in humidity conditions was not perceived by the subjects[45–48]; however, it was perceived as a changed thermal sensation vote and skin wettedness[49] above 28°C and 70% relative humidity[50]. Also, Filingeri *et al.*[48] reported that cold-wet sensation was perceived at a cooling rate of 0.14–0.41°C/s.

Commonly used rational indices are heat stress index (HSI), wet bulb globe temperature (WBGT), Oxford Index, Humidex, predicted heat strain (PHS), skin wettedness, required sweat rate (SWreq), universal thermal climate index (UTCI) and so on, as detailed in several studies[37,51]. These indices were developed with rigorous computations for energy balance in the human body, validated by controlled climate chamber studies with people of specific geographical acclimatization, age group and ethnicity.

However, the results from these studies vary with regional diversity in occupant physiology, behaviour and sociocultural influences[15]. A study[40] showed that people living in rural areas have much greater resilience to change in the thermal environment than in urban areas. Empirical indices established based on subjective responses of occupants are also many, like effective temperature (ET), corrected effective temperature (CET), predicted four-hour sweat rate (P4SR), heart rate prediction (HRP), and so on, and they do not capture the causality of change in thermal sensation. Conducting experiments with different age groups, climatic acclimatization, and medical history is required to strengthen the evidence for appropriate moisture levels for indoor environments.

Clothing and thermoregulation are closely linked to the sense of touch and directly affect thermal and dampness perception[52]. Based on the environmental conditions, clothing on the skin surface affects perspiration, perturbing the body's thermal equilibrium and has implications on thermal stress and performance[43,52–54]. Besides friction/abrasion[43], clothing determines the ease with which it allows heat and moisture exchange with the surroundings[53,54]. The feeling of 'clingy' or 'sticky', 'muggy', 'sweaty', and 'stifling' caused by the interaction of fabric with temperature and humidity[39], is associated with discomfort and affects productivity. Perception is dependent upon relative evaluations and neutral comfort state. As the thermal environment moves from neutral, the evaluation shifts in a negative direction, i.e. sense of discomfort, and when it approaches a neutral environment, the evaluation is positive, i.e. sense of comfort. Heat and moisture exchange from the human body to the surrounding environment is controlled using clothing in several ways. For example, clothing for sprint/ running is expected to ensure quick drying and efficient active perspiration. However, for swimming/diving, the clothing is designed to reduce friction and drag in water, along with reducing heat loss from the body in cold water.

Too much water vapour loss/dehydration can affect cognitive performance, causing short-term deficits like memory loss, problems with visual perception and mood fluctuations. Moisture in a spa or hot springs is often considered therapeutic due to its impact on the body's regulated blood flow and functioning. However, many studies report that humidity in the air increases irritability and decreases productivity, happiness and satisfaction[55,56]. On the other hand, high relative humidity variations were related to the number of hospitalizations of people suffering from mental distress[57,58]. These studies need further examination for causality with varying personal, social and cultural factors.

Water vapour in the air is one of the most critical determinants of perspiration and thermoregulation. Even though moisture has been identified as an essential parameter for thermal comfort, there are few detailed studies investigating dynamic indoor moisture variation, factors determining it, and its impact on occupant health and wellness. Conducive indoor humidity levels for occupant comfort need to be maintained for various building typologies, climate zones and activities. The diurnal/seasonal humidity exposure regulation through passive design of indoor environments needs further investigation and implementation, particularly in the context of climate change.

Due to its direct tactile interaction, moisture levels directly influence thermal comfort, skin-related (IAQ) and respiratory comfort. There is a need for a detailed investigation into this domain, particularly in the emerging context of wellness.

Humidity and taste

Water, through saliva on the tongue, is fundamental to taste perception in human beings. Moisture content in food is a determinant of its quality and taste. Optimum moisture content in cereals and packaged food is essential for nutritional value and consumption. Also, moisture content determines the shelf life of food items. Many traditional communities have practised the desiccation of fruits and vegetables for preservation and consumption. On the other hand, preservation in cold storage (ice), corresponding to lower humidity levels and temperatures, is practised widely in the present-day context.

Changing environmental humidity influences the activity of human taste receptors, as highlighted in many studies. The changing atmospheric pressure is related to decreased environmental humidity levels. As the air becomes drier, the sensitivity and activity of taste receptors decrease. Studies on taste show that the response to salt and sugar in the food decreases with the rise in altitude (implying drier air). This significantly impacts food prepared for onboard aircraft catering[59,60], as it operates at higher altitudes. Food prepared to be served in aircrafts generally has more salt and sugar when compared to food prepared for on-ground use. Also, the response to specific flavourants and chemicals used in food reduces as we move higher in altitude[12,61].

Since sensory response to food taste is impacted by atmospheric humidity, food habits may differ in different climatic/microclimatic zones. Also, it has been found that the air in conventional building typologies is drier than in vernacular building typologies for the same outdoor environmental conditions[62]. A change in dietary habits is expected in occupants of these dwellings, further impacting health outcomes like blood pressure and cholesterol levels, thereby impacting physiological wellness. The perception of taste is important for dietary habits, and has a direct role in ensuring comfort, productivity and wellness.

Humidity and sight

The faculty of sight perception is primarily related to the eyes. Humidity/water vapour in the air is essential to keep the eyes moist, remove dirt from the eyes and have clear vision. While ice and water are visible to the human eye, water vapour is not visible to the naked eye.

However, its impacts are perceivable in the form of dampness in buildings, relative humidity in the air, fog, smog and so on. Moisture on material surfaces is generally associated with condensation (window panes, walls and other surfaces) and is associated with sick building syndrome, majorly observed in the case of mechanically ventilated buildings. Proper regulation and control of moisture condensation is vital, as it may promote microbial growth and spread, leading to an unpleasant odour[15,17,63]. It also acts as a facilitator for dust settlement on surfaces[64].

Dampness in buildings is generally visible on indoor surfaces as a result of chemical (efflorescence, discolouration, etc.), physical (disintegration of material, bloating, etc.), and biological (visible patches of fungi, mould, etc.) interactions with water vapour/water in the building element and indoor air. In indoor environments, dampness, attributed to improper ventilation, causes a change in occupants' attitudes, beliefs and actions attributed to fear of ill health[15,17], causing discomfort and distress. Occupants living in such environments complain of irritation, and are concerned about cleanliness and hygiene[15]. The visual discomfort caused by discolouration of walls and the growth of moulds can lead to discomfort, thereby causing indirect neurotoxic symptoms and health impacts[17]. The pathways linking the health impacts of dampness in buildings resulting from exposure to water and water vapour on building elements are described in Figure 2.

Studies examining the impact of water-related interactions in the built environment on humans are crucial. Integrating such studies into building simulation for occupant health and comfort can help understand overall wellness of the occupants in a built environment.

Discussions

Wellness and its association with sensory perceptions

The terms health, well-being and wellness are often interchangeably used in the literature. While health and well-being refer to being free of illnesses, wellness is a multidimensional concept defined as a way of life to attain optimal health by integrating body, mind and spirituality[65]. It includes physiological, psychological/emotional, social,

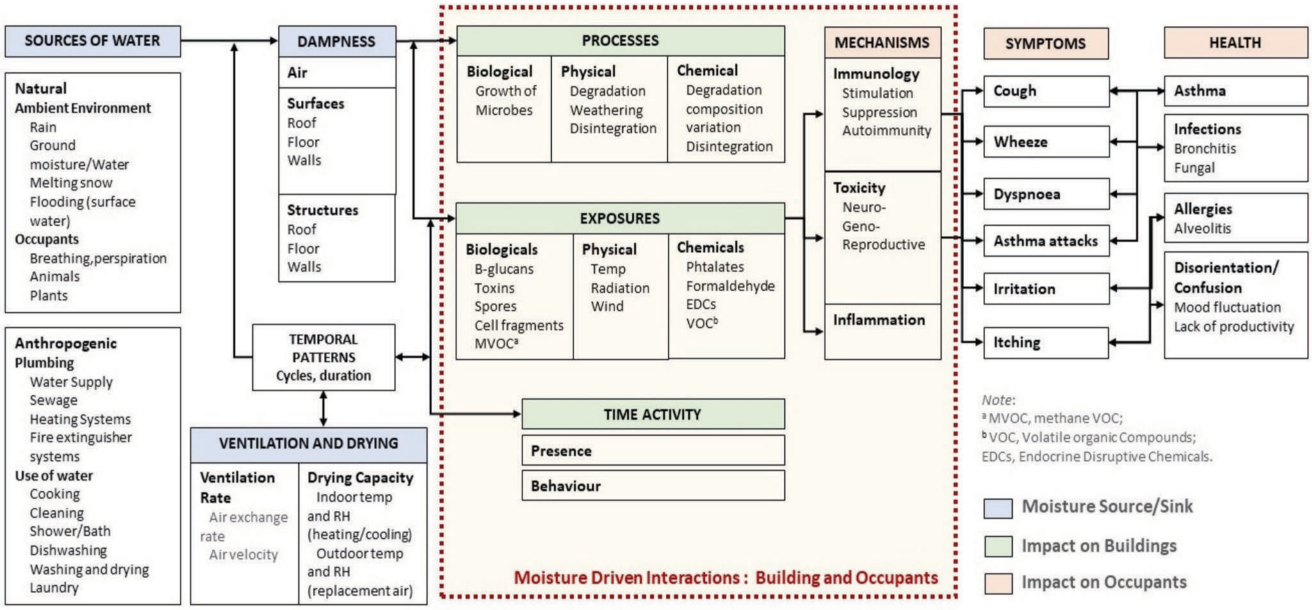

Figure 2. Pathways linking sources of dampness with health, highlighting moisture-driven interactions between the building and occupants (adapted and modified from ref. 22).

intellectual, spiritual, occupational, environmental, cultural and climatic factors[66] that simultaneously determine a balanced living.

Wellness for an individual can be defined as a state of peace and/or contentment achieved through physiological health (body), psychological composure and spiritual balance (mindfulness), social integration (society and profession) and intellectual enrichment facilitated by a conducive built environment.

The eco-systemic approach to understanding wellness (as part of planetary wellness) reflects the interactive elements of the internal and external environments for human existence[67]. Wellness manifests through a conducive balance between the self, society and the natural environment[68].

The self or internal balance can be attributed to physiological health (or well-being) and individuality. Physiological health is closely linked to the degree of freedom exercised by the individual while performing everyday activities like bathing, walking, sleeping, etc. Individuality is derived from an individual's outlook, composure and temperament towards life. It could have psychological, spiritual, intellectual and experiential influences attributed to a conducive social harmony, cultural value and occupational/professional alignment.

The external balance is derived from coherence between the natural (influenced by environmental and climatic) and social environment, both of which depend upon the nature of the built environment. The built environment comprises an altered natural environment adapted to human beings' social/cultural requirements, vocations and conveniences. The interaction between elements of the built environment and human beings determines wellness for humanity and the planet. Wellness, thus, is the fundamental pursuit that connects the built and the natural environment, and underlies sustainability. Positive experience in nature has a profound impact on appreciating the interconnectedness between nature and human beings, thereby protecting it. It can be observed in the distinct functioning of indigenous vs modern society. Planetary wellness is crucial for human wellness and vice versa[69]. Comfort and health are important indicators of wellness, manifested through sensory response and perception. One of the treaties on health states that

> '*Connection to the source (consciousness), indriya or sensory faculties (vision, hearing, smell, taste, and touch) and psyche should be working well in coordination with the body, and the person is in a state of bliss*'[70].

From a philosophical perspective, wellness can be viewed as an outcome/indicator of a harmonious balance between an individual's mind, body and spirit. From an operational perspective, in the built environment, wellness can be perceived as a state of calm/harmony experienced by an individual in relation to prevalent living conditions. This experience is essentially what the individual thinks/feels and can be derived from a combination of momentary and/or conditioned sensory (physiological) and emotional (psychological) experiences. Therefore, it is crucial to understand sensory perception and responses attributed to any environmental parameter for its contribution to human and planetary wellness.

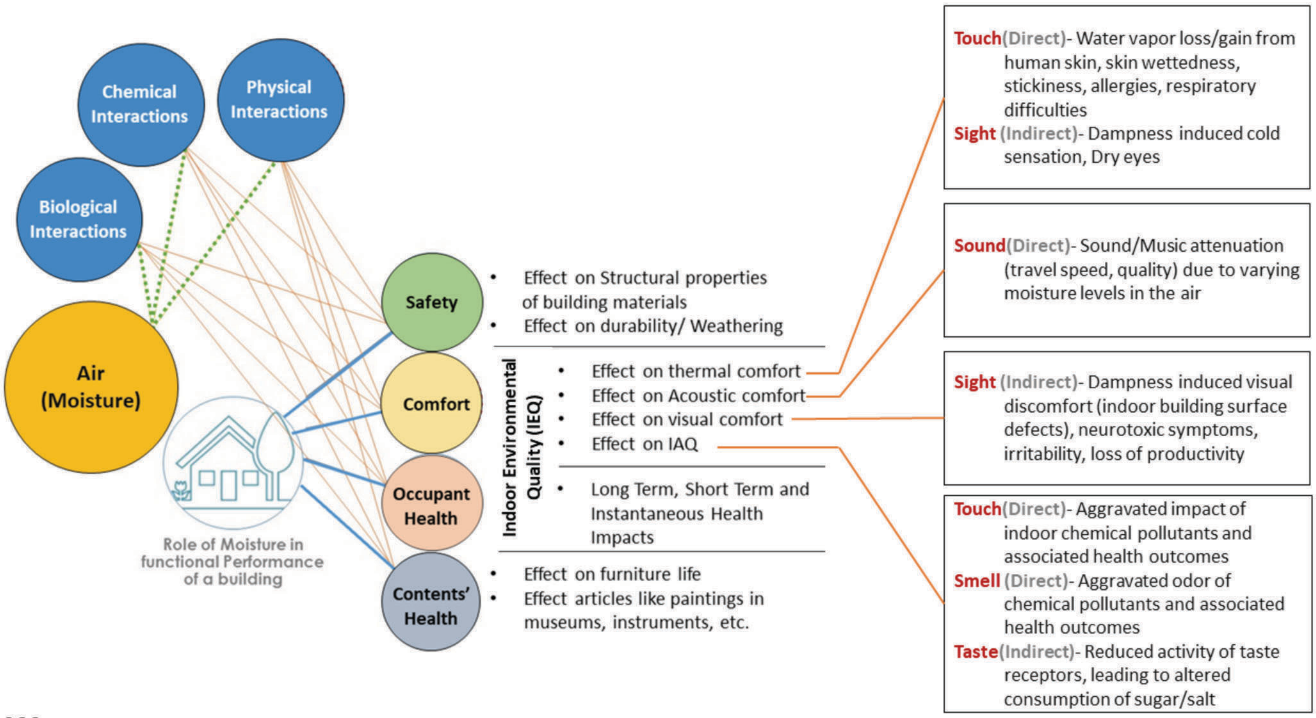

Figure 3. Association between indoor environmental quality parameters and sensory perception.

The case of optimum humidity for comfort, health and wellness

The challenge is obtaining the optimum moisture levels, as too little can cause severe ailments like respiratory difficulties, or too high can cause skin discomfort, irritation, etc.[20–22,71,72]. Relative humidity between 40% and 60% is optimum[73] due to less proliferation of microbial contaminants in this range. The scientific validity of the range, however, remains debated for numerous reasons[74]. The indirect psychological effects are not easy to trace but are profound and subject to increasing scientific scrutiny. All the human senses are impacted by varying humidity levels, as explained in Figure 3, impacting indoor environmental quality (IEQ)[63] and determining health and wellness.

Moisture in the air and its interaction with building materials impact occupant comfort, leading to ill health, stress and productivity loss. The regulation of indoor moisture is crucial in different vernacular and modern buildings. Recent studies have revealed that various building typologies maintain varying indoor humidity for the same external conditions. This primarily has been traced to the interaction of indoor surface finishes with moisture[62,75,76]. Moisture buffering is a surface phenomenon in which the building material releases and absorbs moisture from the indoor air to regulate relative humidity[77]. With the increased hygroscopicity of vernacular materials, moisture buffering[78–81] is eased, resulting in better moisture regulation and balance. However, in modern buildings, with water-repelling coats, this interaction is constrained, giving rise to surface condensations, dampness, growth of fungi and moulds, etc. Air has a wide range of suspended particles that hold water vapour. Indoor air pollutants adhere to the moisture in the air exposed to occupants (touch or/and smell) and have several health implications. Their interactions with each other and water vapour may vary with their chemical and biological constituents. Moisture in the air is a driver for fungal bio-aerosol exposure in indoor environments, causing infections[82].

The effects of prolonged exposure to extremities in moisture (in the form of high humidity or dampness/or dry air) on human health can be direct or indirect[22,73,83–85], has been illustrated in Figure 4. The direct effects include symptoms like cough, wheezing, dyspnoea, asthma attacks, irritation of the skin and eyes, and itching (short-term effects), leading to diseases like asthma, bronchitis, fungal infections, cardiovascular diseases and allergies (long-term effects). The physiological response of the body (instantaneous effects) may lead to thermal discomfort, dryness, chapping of the skin, irritation, itching, difficulties in breathing and redness of the skin[22,85,86]. All the impacts illustrated are crucial to determine the state of health and mind, hugely impacting everyday human activities and productivity.

Scientific studies show a clear correlation and similar trends for the acceptance and behaviour of individuals exposed to certain odours. A group of children, when

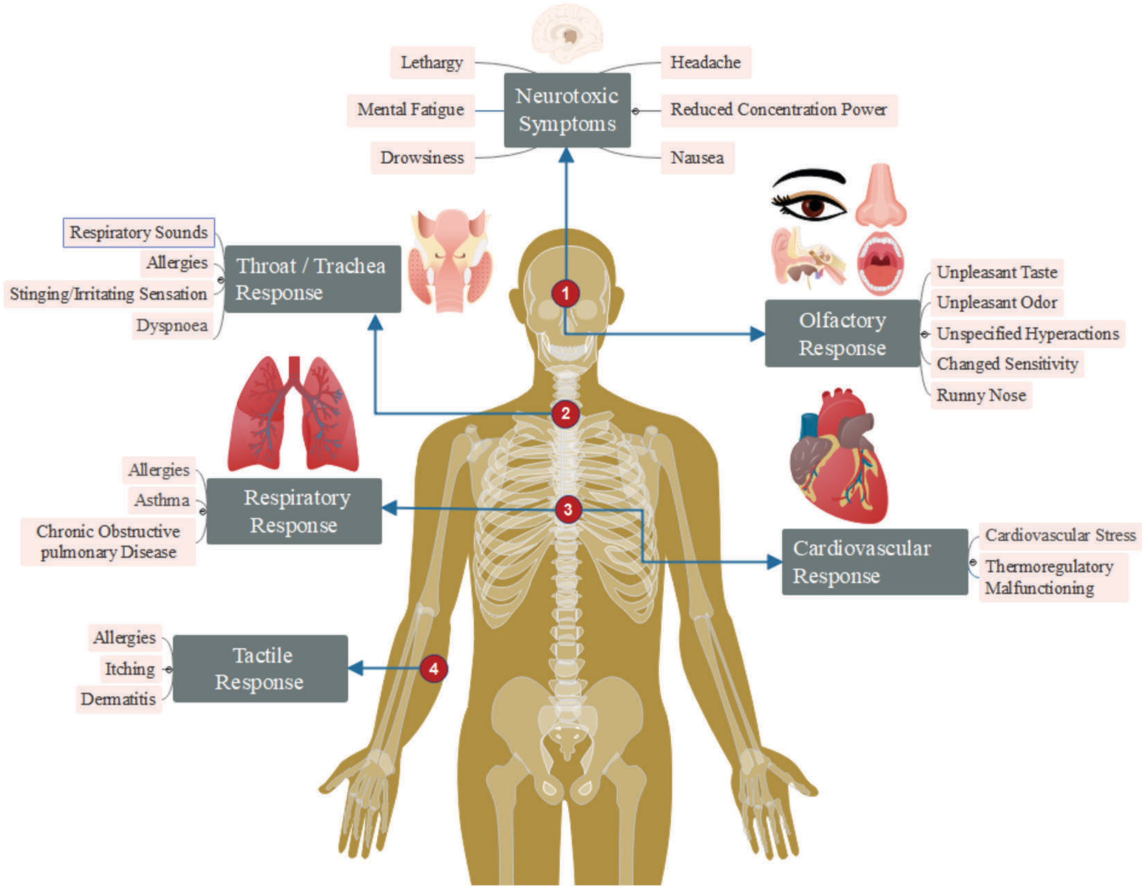

Figure 4. Health impacts associated with improper humidity.

exposed to several kinds of smells, i.e. sweet, bitter, neutral smells, etc. show consistent facial expressions, suggesting more acceptability to specific smells[87], which can be traced to primal hard-wired responses.

Research gaps and way forward

Comfort is an essential criterion for determining the built environmental quality and health. Specifically, thermal comfort is associated with the perception of water vapour with varying environmental and personal factors and adaptation. Thermal comfort determined by varying moisture levels in the indoor air directly impacts heating/cooling load; therefore, its relation to energy consumption and application in passive design needs to be understood in detail. A framework to assess wellness in a built environment and health outcomes with exposure to humidity needs sustained interdisciplinary research. Water vapour in the air is the fundamental route for affecting the functionality of the human senses, as discussed in this article. Hence, examining sensory responses to manifestations of varying (spatial, temporal) humidity trends in the built environment (varying with personal, cultural, social, etc. factors) needs research. Some research gaps arising from the examinations of water vapour and sensory perception that need investigation in the context of wellness include the following:

Smell: Moisture plays a critical role in the dispersion of odour, directly affecting our moods, productivity and sense of well-being and health. Freshness in the air is directly correlated with odour. Material porosity, vegetation, prevailing climate, wind and ventilation play a critical role in retaining and disseminating pleasant/unpleasant odours. Studies examining freshness in the air, as influenced by the diversity of factors in the built environment, need to be conducted. With the stimulation to the sense of smell, the impact on the olfactory experience of human beings with exposure to water vapour needs examination.

Touch: The human skin surface is always surrounded by and interacts with water vapour in the air, determining heat losses/gain and perspiration. Water vapour in the air inhaled through the nostrils and reaching the lungs through the windpipe, impacts the ease of breathing and respiratory health. Further, building materials regulate variation in indoor air moisture, which is directly associated with comfort and health outcomes (majorly skin-related and respiratory), which needs to be understood in detail. The pathways associated with the health and productivity impacts (Figures 3 and 4) and their applications in built environment design need further scrutiny.

Sight: Functioning of human eye is impacted directly by the amount of moisture in the air. Also, it is responsible for the cleansing of the eye. Complaints of dry eyes, irritation and redness may be traced to the constituents of the air, primarily due to moisture and the presence of toxins/dust, etc. The association of varying moisture levels in different indoor (as affected by building material/typology) and outdoor environments with eye health needs investigations. Scrutiny into design guidelines for healing using water in biophilic design (altering humidity levels-cooling/humidification) is very relevant and needs development. Technological interventions to reduce moisture-associated defects in buildings, like dampness and sick-building syndrome causing aesthetic/visual discomfort, need investigation.

Sound: Water vapour in the air determines its density, which determines sound propagation speed. The acoustic properties of materials depend on the amount of moisture in the material. Investigation into the acoustic performance of hygroscopic, low carbon building materials (earth, lime, etc.), with variation in moisture content diurnally, seasonally and in different climatic zones, is important to be ventured into. Also, exploring water vapour to mitigate noise pollution, in conjunction with vegetation and suitable surface finishes (materials), could potentially impact the built-environmental design guidelines and needs adequate research.

Taste: Environmental humidity impacts taste perception, evidently witnessed at higher altitudes on aircrafts. Design strategies to regulate indoor environments to ensure optimum response of human taste receptors, thereby impacting food consumption and lifestyle needs examinations.

Conclusion

The wellness of human beings is multidimensional and is intrinsically linked with the human physiology, psychology, spiritual and cultural aspirations, and outlook of an individual. Pathways relating wellness to built environment design are complex at operational levels. The built environment design sensitizes and imbibes an involuntary or voluntary sense of wellness. Sensory responses are governed by physiological and mental/personality interactions with the built environment. Water vapour in the air is an important parameter due to its abundance, constant exposure to human beings and dynamic occurrence trends. Presently, water vapour or humidity in the air is acknowledged to impact comfort and health but has not been explicitly incorporated in building/built environment design guidelines.

In the course of this article, an attempt has been made to collate and explain the interdisciplinary aspects of sensory response to water vapour in the built environment for wellness. Inferences from the article may help design environments (and buildings) to attain specific functionalities or enhance them by the appropriate regulation of water vapour.

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