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A theoretical framework for classifying occupant-centric data streams on indoor climate using a physiological and cognitive process hierarchy

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ABSTRACT

New and pervasive information and communication technologies have made it possible to capture a large range of continuous data from, or close to, each individual building occupant. These occupant-centric data streams may include subjective votes, evaluations, complaints, control actions, physiological measurements such as heart rate or pupil size, physical measurements of skin temperature or local draft and air temperature measurements, and much more. Currently, considerable resources are put into studies that focus on the development and potential uses of such systems, while the origin and nature of the collected information which is embedded in the data is poorly investigated. In this paper, we propose a taxonomy for the classification of occupant-centric data streams, developed through the application of established theories and categories in environmental and market psychology. The proposed framework organises five data source categories and links them to four levels of physiological and cognitive processes, making an explicit connection between data and embedded information attributes. The framework, originally developed to classify continuous occupant centric data in the domain of indoor climate, can also bring insights that might help explain known gaps and challenges in different models and theories that aim at predicting individual satisfaction with indoor climate conditions.

1. Introduction

The diversity of individual occupants' evaluation of indoor environmental quality, and in particular the assessment of the thermal comfort conditions in the indoor climate, is an acknowledged and established fact. Because comfort is defined as "*the condition of mind that expresses satisfaction with the (thermal) environment*" [1], it's assessment is necessarily a *subjective* evaluation, i.e. "*based on or influenced by personal feelings, tastes, or opinions*" [2]. The collection of the subjective evaluation of the experience with the indoor climate is therefore a key process for the study and assessment of diverse comfort demands. These ultimately impact the operation (and design) of our buildings and occupants are known to have a high influence on building energy use [3]. For example, when it comes to energy use for building climatization, most office buildings in Europe and North America are controlled using a tight temperature dead-band between heating and cooling set-points. One study found that reducing the heating set-point from 21.1 °C to 20 °C saves an average of 34% of terminal heating energy, while increasing the cooling setpoint from 22.2 °C to 25 °C, leads to an average of 29% of cooling energy and 27% total HVAC energy savings [4]. Furthermore, widened temperature bands, made possible by the use of fans or personal controls, can result in HVAC savings in the range of 32%–73%, depending on the climate. The occupant's satisfaction (or dissatisfaction) with an increased range of indoor climate conditions, and the interplay between occupants and their individual climate control opportunities may lead to substantial reductions (or increase) in energy use. In this perspective, solutions which make it possible to loosen the temperature dead-bands while assuring, at the same time, occupants' satisfaction may be a significant contribution toward carbon–neutrality in the built environment [5].

The recent advancements in information and communication technology (ICT) that have made it possible to deploy sensors and software in common objects all around us, and to network them with the purpose of connecting and exchanging data, have brought new possibilites to the field. They offer a great possibility to record and study the comfort diversity by getting data "close" to the individuals, with the aim of obtaining a better knowledge of the relation between occupants and their satisfaction. We can define the large spectrum of information related to, and originating from, the occupant, that can be used to support occupant-centric building control, design, and operation, as "Occupant-centric data" (OCD).

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Nomenclature

Acronyms

CSOF	Continuous Subjective Occupant Feedback
HVAC	Heating, Ventilation & Air-Conditioning
ICT	Information and Communication Technology
OCC	Occupant Centric Control
OCD	Occupant Centric Data
OTS	Observed Thermal Sensation
OVS	Occupant Voting Systems
PIR	Passive Infrared
PMV	Predicted Mean Vote
POE	Post Occupancy Evaluations
PPD	Predicted Percentage Dissatisfied
RFID	Radio Frequency Identification
SPS	Satisfaction Polling Station
TSV	Thermal Sensation Vote

Occupant-centric building control, design, and operation is representing a relevant perspective shift for the development of new strategies for building design and operation [3]. The research community has started to take advantage of this opportunity, and an increasing body of knowledge has been generated in the most recent years by developing and adopting a wide range of systems and platforms to collect different types of OCD. The research and innovation in the field has until now worked primarily to develop solutions that can collect and visualize such data for the purpose of building control and operation, leading to the development of so-called occupant centric controls [6]. A few commercial products are already available in this category, such as the voting control system Comfy and the Cozie App for registering occupant opinions [7,8].

Several scientific reviews also cover concepts that are within or overlap with OCD. The emerging field of Occupant Centric Control (OCC), recently reviewed by Park et al. [6], refers to controlling building systems based on presence/absence data, data from the occupant, and human-building interactions. Jung and Jazizadeh [9] reviewed Human-in-the-loop HVAC operations, referring to human interactions related to the dynamic behaviour of occupants. Khan et al. [10] presented a thorough review of Occupant Voting Systems (OVS), which also included a framework for characterization.

In the literature, a large range of terms are used to identify and characterize what we here define as OCD, ranging from the measurement of physiological reactions though body-level sensors, location and motion data, information linked to occupant interactions and occupant opinions collected with various interfaces. However, so far, no thorough effort has been made to study, from a more theoretical perspective, the intrinsic meaning, information attributes, and categories of the different types of occupants' data. *Occupant control actions*, *occupant complaints*, *occupant preferences*, *occupant sensation votes*, *occupant satisfaction*, *occupant feedback* are just a few examples of terms used without clear definitions, and often in an interchangeable way. A closer examination of the origin of the above-mentioned information types raises questions about how subjectively submitted information differs from objectively measured information, and how *control actions*, *complaints* and *satisfaction evaluations* all may relate to the classical terms of comfort or acceptability.

In a recent study [11], we developed and tested a system for collecting data on occupant actions and satisfaction. The design of such system was based on a literature study of existing systems for Continuous Subjective Occupant Feedback (CSOF) regarding indoor climate. However, during the process behind this study we were forced to investigate, beyond the current, established knowledge, the link between data sources, the natures of the collected occupant data and the embedded information. This challenge formed a basis for the reflection and the effort, presented in this paper, to establish a comprehensive classification system capable of making explicit the different nature and information value embedded in different OCD streams.

The aim of this paper is, therefore, to explore the concept of (continuous) occupant-centric data and to reflect on the type of information attributes of the different types of data collected from the users. Since an understanding of these topics, as described in the next Theory section, is crossing the borders between established theories within the fields of (thermal) comfort, market psychology, and environmental psychology, we believe that a common ground needs to be established and a clear theoretical framework derived to provide a shared platform and vocabulary in this multidisciplinary research effort. While we developed our study starting from the analysis of the hygrothermal climate and thermal comfort, we are convinced that the concept of matching psychological processes and information to occupant centric data can be applied to all the dimensions of indoor climate. The way the human sensorial apparatus functions is similar across the domains of indoor climate, and the signals are processed across the body and in the brain in similar ways. Most of the cases and explicit links made in this study refer to the hygrothermal domain, because they work well as explicative material to guide the reader through our research endeavour.

In a nutshell, the main outcome of this study is a novel theoretical structure to understand the different nature, values, processing levels, and information attributes, of a series of OCD. This construction is schematised though a taxonomy for the classification of occupant-centric data in the domain of indoor climate, covering both objective and subjective information. We aimed in particular at establishing a framework, grounded in theories and categories developed in environmental and market psychology, which can make explicit and justify the link between data collection, information embedded in the data, and human physiological and psychological processes.

While recording and processing continuous streams of digital information about the physical quantities of the space is a well-established process, with plenty of standardised and tested procedures, continuous information streams on and from the occupant is a new domain of science that has emerged in recent years. It is therefore natural to see that more fundamental knowledge and systematization is still needed in this recently born field. Though we don't have the ambition to promote the proposed framework as the only possible, nor as the best one, to classify occupant-centric data, we believe that it can be useful to foster a more conscious use of continuous occupant-centric data as an important input for the correct understanding of the occupants' evaluation of the indoor climate.

2. Theory

The understanding of the theoretical contexts behind the information embedded in OCD is highly important to ensure that the common data sources known in classical indoor (hygrothermal) climate research, the tools used to collect such data, and the nature of the collected information are fully aligned.

In the first part of this Theory section we present relevant theories within the fields of environmental psychology, general psychology, and market psychology that led us to organizing the different types of occupant-data in relation to the information embedded, and therefore provides the foundation for the structure of the framework that we have developed, presented in Section 3. In the second part, we revew, describe, and classify commonly used data sources (and tools) linked to building occupants' data, and create a shared vocabulary that is used for the description of the framework. In processing the different sources of occupant-data, we organize them in a form that is functional to the development of the proposed taxonomy. For the sake of conciseness, we do not report in this paper a table nor many details of the studies available in the literature that we have analyzed, as more information on such studies can be found in another recently published article [11].

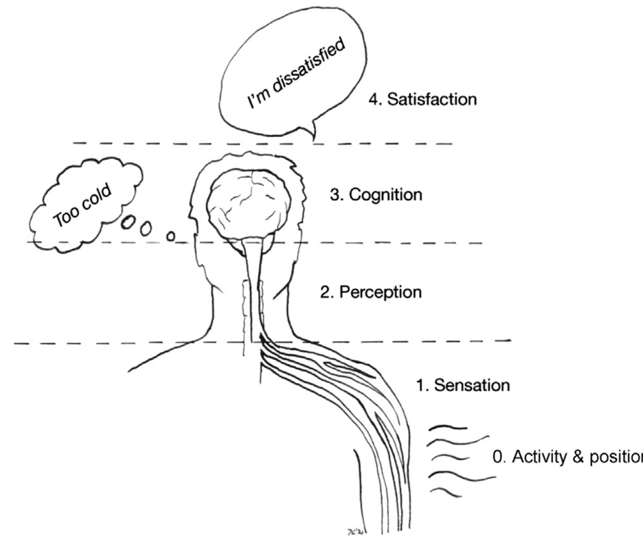

Fig. 1. Schematic of psychological concepts for the phases and thought processes involved in sensory processing of environmental input.

2.1. Physiological and psychological processes

While a large number of studies in the indoor climate field [12–16] refer to *subjectiveness* or *subjective feedback* as a key characteristic of the collected information from the occupant, the term is rarely elaborated on or defined in rigorous terms, and employed as used in the common language. It seems clear and reasonable that when a building occupant or a laboratory test subject is asked to provide information about the *personal opinion* of the indoor climate, the information will in all cases be subjective. From a psychological perspective, the reason for this is that the individual has made an active decision and chosen what to answer, i.e. a cognitive thought process has occurred. However, when speaking of the different data streams that can commonly be collected in buildings, the question of subjectiveness becomes more complicated. Further clarification is needed for describing how subjectiveness is linked to cognitive processes in human beings to assure that this term is used with a sufficient understanding of its meaning. The same background discussion is needed for several other phrases, such as *satisfaction*, *comfort*, *perception*, *sensation*, and *consciousness*, which are rooted in human psychology.

To investigate this point and provide a new understanding of the information values embedded in different for occupant-data, we present in this section a series of psychological concepts for the phases and thought processes involved in sensory processing of environmental input (see Fig. 1). We owe the information reported in this section to established theories within the fields of environmental psychology, general psychology, and market psychology, with a particular link the approach proposed in some recent research efforts that have launched the idea of viewing building occupants as *consumers of indoor climate* [17].

2.1.1. Sensation and perception

The terms *sensation* and *perception* have been used in thermal comfort literature for many decades. *Thermal sensation* is understood as a sensory experience – a psychological response to the state of thermoreceptors in the our skin [18]. In some cases, the term *perception* is used instead of *sensation* with a similar meaning [19–21]. The use of these terms in thermal comfort theory is somehow within our common understanding of these expressions and little or no questions have been raised on how these psychological terms are defined within the field of psychology.

The definition and description of these terms in the field of environmental psychology differ significantly from how they are defined and used in thermal comfort research. According to Kopec [22], *sensation* in general terms refers to all the sensory stimuli which are presented from our nervous system to our brain at all times. In other words, the *sensation* is directly related to the signal of hot or cold stimulus, gathered by thermoreceptors in our skin. According to Gazzinga et al. [23], *sensation* refers to the early processing of a stimulus. The mental representation of the same stimulus is called *percept*. *Perception* is thus the process of constructing the percept and it is understood as the first phase in our overall thought process, which is the process of creating meaningful patterns from raw sensory information. We have therefore entered *sensation* and *perception* as the first and second stage for human processing of environmental input in Fig. 1. Through perception, our brain combines and interprets sensory information from numerous sources, including past experiences, motivation, current emotional state, arousal, as well as the raw data from our senses. Neuroimaging studies have helped reveal that extensive interaction takes place between the signals from different senses much earlier in the processing pathways than was previously imagined [23]. The total picture of our environment combined with our internal state is then represented for further processing in "higher" levels of processing and decision making.

The process of *perception* is highly information intensive and energy demanding. The blood supply to the human brain can only provide enough energy to keep 3% of the braincells active at any moment [24]. Therefore, a hard, prioritization process is continuously on-going determining which information is to be processed. The brain will to a great extent disregard the information gathered by our senses and simplify the processing task by relying heavily on assumptions and previous experiences [25]. Most of our perceptions and behavioral responses never reach our conscious awareness, and what does reach our awareness is never an exact replica of the original stimulus which is sensed by our nervous system [23]. A large part of the perceptive process is therefore unconscious. Both conscious and unconscious perceptions can cause reactions. In some cases, a subliminal perception can cause a biological or learned reaction, which then catches the attention of our conscious mind: a cold draught producing goosebumps may be an example of this [26]. Direct reactions to perceptions are however in this case not considered *subjective* actions, as they do not involve cognitive decision-making or processes of free will. Habituation and learning may change the way we react to stimuli over time [27].

The understanding of the terms *sensation* and *perception* seems to be poorly aligned across the academic fields of thermal comfort and psychology. The psychological understanding of these phenomena emphasizes how sensory input from one sense (e.g. the thermal sensation) is combined with information from other senses and information about our current state at an early stage [23]. An individual's perception of the thermal environment (e.g. warm or cold) will not be solely founded on the thermal sensation but will be built on a combination of information regarding thermal environment, current thermal state, metabolism, alertness, motivation, past experiences, and possibly many other domains. Even sensory input regarding light and smell may be relevant [22]. The definition of sensation as an early stage processing of a stimulus implies that humans can have *conscious perceptions* about the environment, but they may not have *conscious sensations*.

Therefore, considering these psychological processes and the way they are named, it is formally incorrect, at least from the perspective of psychology, to define, for instance, a *thermal sensation vote* – but this should be rather called a *thermal perception vote*, although the act of voting will in all cases also be cognitive. This description of human perception supports recent research findings within the field of thermal comfort, such as the *alliesthesia concept* [28] and the fact that there is an effect of non-thermal factors on thermal comfort [29]. Perception is not only highly subjective, but also consists of a myriad of variables that affect the interpretation.

2.1.2. Cognition

As the brain continues to organize information into patterns of understanding, we move beyond perception into cognition. Cognition is defined as "*the mental action or process of acquiring knowledge and understanding through thought, experience, and the senses*" [30]. Broadly speaking, it is the process of thinking, knowing, or mentally processing information, including memory, attention, perception, decision making, and action. Environmental cognition is a more specific concept that refers to how people understand, diagnose, and interact with the environment [22].

For the purpose of this study, we define cognition as the third phase of the process involved in sensory processing, after perception (see Fig. 1). In this phase lies problem solving, decision making, and goal-oriented behavior. Decisions made and actions initiated in this phase can be called *subjective*, as they are based on a conscious and logical thought process and free will. Examples of such decisions and actions in relation to indoor climate may be the choice of opening a window or putting on a sweater, or the choice of which scale unit to answer in a questionnaire regarding thermal sensation. The choice of discussing aspects of the thermal environment with others will also lie in this stage. Possible emotions and attitudes occurring in such a discussion are however involved in what we in this case choose to define as the third phase of the thought process, *satisfaction and attitude*.

2.1.3. Satisfaction and attitude

To provide *Satisfaction,* we have to do or make "enough" [31]. Satisfaction can be said to be similar to *attitude* but at the same time clearly refers to a more superficial and object-oriented context. *Attitude* is the mental and neural state of readiness to respond in a certain way. Attitude is a broad psychological concept which consists of three pillars; cognitive (thinking), affective (feeling), and behavioral (doing). Even though we here define it as a higher order thought process, our attitude can strongly influence our perceptions [32]. While attitudes can be politically or ethically based, satisfaction refers more directly to whether our expectations to a certain object, service or experience are fulfilled [31]. However, satisfaction is not simply performance processing, or emotion states such as happiness. It contains components of both judgement (cognition) and affect (emotion) [31]. Research regarding satisfaction, or more specifically customer satisfaction, mainly originates from the field of market psychology. The goal is often to understand how consumers evaluate consumables and which aspects are important to increase the possibility for them to repeat-purchase a product. Another goal is to investigate the determinants of employee satisfaction. The satisfaction with the indoor climate may be seen as a part of this. Occupants who are satisfied with the overall environmental quality of their workspace are widely assumed to be more productive [33]. In this view, occupants are being regarded as consumers of the product (building) and as such, entitled to be satisfied with the indoor environment. Classic indoor climate theory has focused on determining which physical conditions occupants report to be *dissatisfactory* or evaluate as *unacceptable*. However, this verdict has been seen as a deterministic threshold and not as a heavily psychological phenomenon. The focus has been put on the *sensation*, but seldom on the other psychological determinants influencing our *satisfaction*. When the building occupant is identified as a consumer of indoor climate, this opens for the use of market psychology and theory of customer satisfaction for understanding the psychological processes for satisfaction evaluation in an indoor climate perspective. To date, not much research has investigated the theoretical implications of this view, although they may be many and important.

Without entering a long digression that would lead us to explore in details a series of established concepts in psychology, such as the "*disconfirmation paradigm*" [34] (the relationship between expectations and performance of a consumable [35–37]), the "Kano's model" [38] for customer satisfaction based on a classification of the type of relationship between specific product qualities and overall satisfaction (with the Bonus factors, the Basic factors, and the Proportional factors [17]), we can summarize that the different and articulated processes behind *satisfaction* are thought to be primarily cognitive, though the affective basis of satisfaction is, at least partly, understood as not to be fully under conscious control.

Satisfaction is thus the summary state of a psychological process. It results at the end of the consumer's processing activities and not necessarily when the product or service outcomes are observed. Satisfaction evaluation is here defined as the fourth phase of the process involved in sensory processing, shown in Fig. 1. It is a voluntary process and not a necessary part of sensory processing, but rather an evaluative step which often is performed during or after then consumption of the product, which in the case of the building can be the indoor climate. Nevertheless, we also define satisfaction with indoor climate conditions as the ultimate goal when creating indoor climate conditions, after health and productivity.

2.1.4. Conclusive remarks on physiological and psychological processes

By applying established theories within different fields of psychology, we have in this section made explicit a hierarchical structure, organized in different levels, that describes the sensory processing, moving from the physiological reactions to the psychological processes (as visualized in Fig. 1). We need to observe that much of the terminology used in this structure (*sensation, perception, cognition,* and *satisfaction*) is often seen in the current (and established) research in indoor climate, though we highlighted here how the attributes behind these terms can be quite different in psychology and in indoor climate research. With attributes we intend here the following dichotomies: the physiological vs. psychological nature; the subconscious vs. conscious nature; the objective vs. the subjective nature; and the reactive vs. evaluative nature of the process. By drawing and defining the flow of information within the human body using a rigorous set of tags, features, and definitions, we are now equipped with a scaffold to analyze how different data streams concerning occupants can be classified with having in mind the value and nature of the information embedded in these data streams.

2.2. Occupant-centric data streams

A data stream is a continuous ordered sequence of information items [21]. In the case of indoor climate assessment and control, this means continuously sampled information ordered in time, which can be related to the physical environment and, for occupant-centric data streams, to information on and from the occupants. The occupant survey, an important source of occupant data, is not here considered as an occupant-centric data stream since these data acquisition events are not continuous and will therefore be left outside the scope of this study. Continuous measurements of the physical quantities related to the indoor environment are also nowadays enhanced by low-cost sensors and pervasive wireless solutions. A detailed discussion of these measurements is beyond the scope of the present work. Hence, we identified and grouped into five categories, in light of the previously defined hierarchic level structure of sensory processing, the different sources of occupant data. These are visualized in Fig. 2 and described in details the following sub-sections.

2.2.1. Continuous data-streams of physical and spatial data of the occupant

The review of occupant-centric control by Park et al. [6] found that over half of the studies studied so-called occupancy based occupant centric control, meaning that they focus on measured presence/absence of the occupant for control purposes (Fig. 3). When the objective was detecting occupancy counts, motion detectors were either complemented with other types of sensors such as CO_2, acoustics, plug loads, chair sensors, camera-based motion detectors, signals from Bluetooth and WiFi-enabled devices, Radio Frequency Identification (RFID) [39], or a fine grid of motion detectors were used for indoor localization. Temperature sensors, Passive Infrared (PIR) sensors [40,41], cameras, wearable devices, smartphones, ultrasound and other types of devices may also be used for collecting presence or motion data [42]. Although this kind of data in most cases is used for predicting key occupancy metrics such as arrival and departure time patterns for advanced lighting or HVAC control applications, there are several other possible uses. For example, a movement that takes the occupant from a cold place to another place with warmer temperatures may actually embed information relevant for thermal comfort, and a change in the position, or a movement, might actually count as a control action (where the occupant does not control a device, but controls own comfort through a movement), or an adaptation process (very typical also outside the thermal comfort domain, as in the case of glare discomfort where the occupant can turn to avoid uncomfortable positions). Adaptive comfort processes have been found to be relevant to the occupants of all types of buildings, including air conditioned buildings [43], hence the potential recording of this information is of high importance. However, we can argue that on its own, data on the position or on the movement cannot give full information to count, for instance, as the information that can obtained by recording the occupant controlling a device linked to the indoor climate control system. The movement could be a control action, but it can also just be the result of other routines. Another potential issue with the use of cameras and occupant tracking (as well as other collection methods entailing personal information) are the ethical issues concerning privacy and the handling of personal information. Though this is an important and much debated issue, it is not at the core of the debate presented in this study and will not be further investigated here.

2.2.2. Continuous data streams of physiological reactions of the occupant

While measurement of physiological reaction is not a very novel source of information for laboratory tests, the current development in sensor and communication technologies has enabled network connected devices (also known as Internet of Things, IoT) that can be used outside controlled environments to continuously

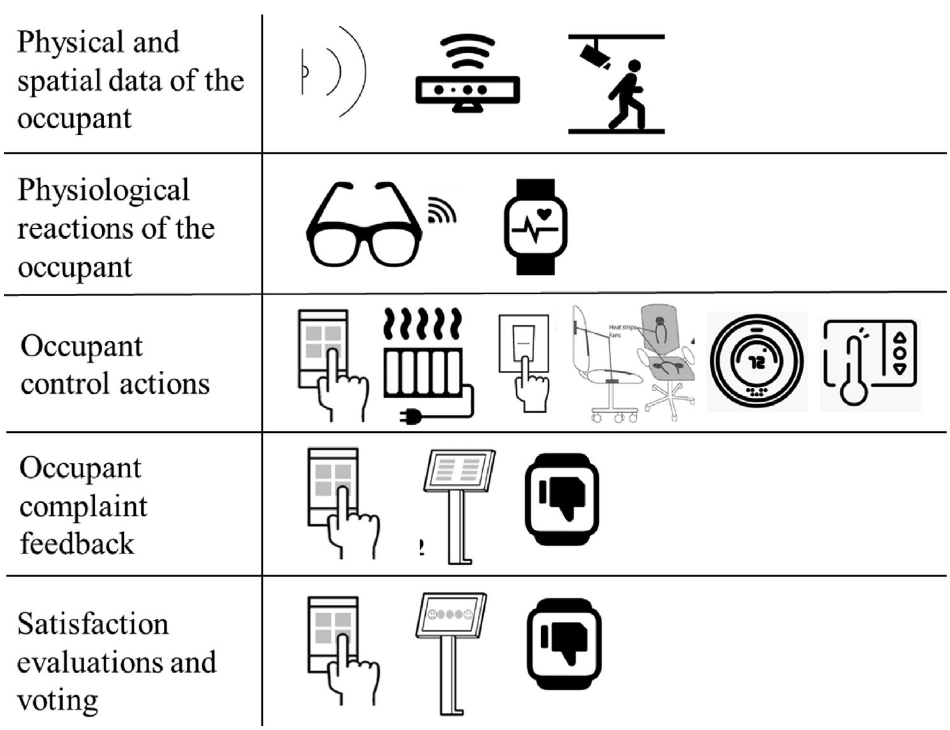

Fig. 2. Data-streams with examples of data collection technologies.

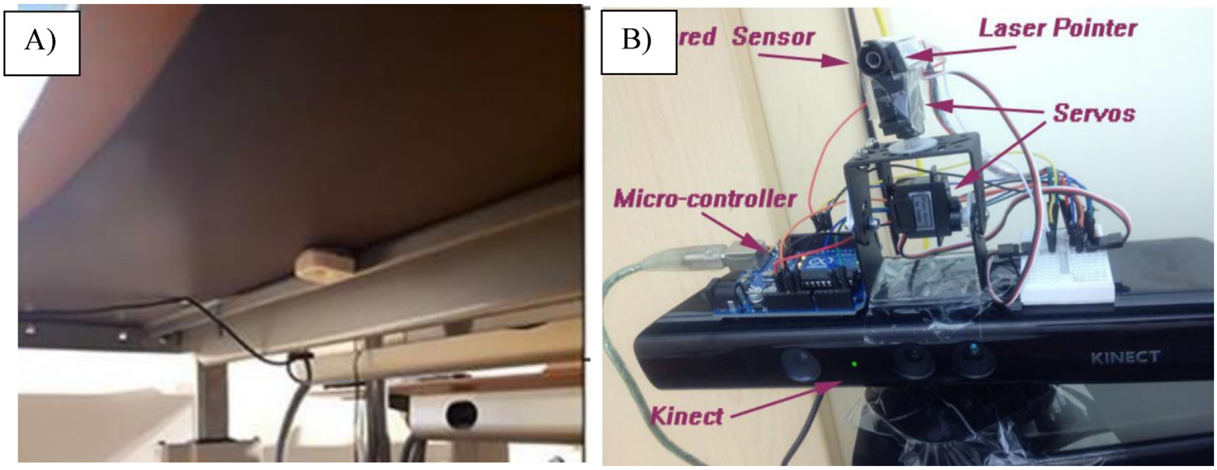

Fig. 3. A) PIR motion sensor mounted below desk for tracking occupancy patterns [40]. B) Infrared sensor and Microsoft Kinect laser scanner for clothing level estimation [44].

sample and transmit body-level measurements that describe the functioning of the human body (Fig. 4). In most cases, wearable devices such as smart watches or wristbands[45,46], or even mobile phones and body sensors [47], are used to monitor physiological parameters such as heart rate, activity, skin temperature, and electrodermal activity (galvanic skin response). In other cases, fixed infrared cameras at the workstations have been used to monitor facial skin temperature to predict thermal comfort [48,49], or 3D scanning devices or motion cameras are used to monitor occupant activity [44] or even body posture or facial expressions. Data streams from occupant physiology have been shown to make a significant improvement in predicting the comfort wishes of individuals, often by developing personal comfort models [16]. These approaches are currently at the research stage and seldom used in commercial buildings. A certain number of studies, such as [44,46,48–50] investigate how physiological reactions in occupants measured with wearable sensors or thermo-imaging can be used for predicting occupant preferences, thus explicitly linking physiological quantities to occupant experience of the indoor climate.

2.2.3. Continuous data streams of occupant control actions

Similarly, to wearable devices, new sensor and wireless communication technology has also made possible a development in data collection from the control actions performed by the occupants (Fig. 5). As the price, size, and convenience of wireless sensing equipment has improved, it has become possible to gather information on occupant interactions with windows and personal environmental control devices such as heaters and fans [53], in addition to the possibility to record through building management systems the changes operated by the occupants on set-point values, for example though thermostats. In some cases, furniture such as office desks and chairs have incorporated personal heaters and fans, as well as internet connection providing usage data [54]. Occupant control actions may also be collected from existing analogue devices in cases where they can be equipped with distributed sensors, i.e. tracking of manual window opening with tactile sensors. Occupant control actions provide important information about the *subjective preferences* of the occupant, especially when held up against information about the physical ambient conditions.

2.2.4. Continuous occupant complaint feedback

Another type of occupant data, which is naturally linked to the previous category, yet conceptually different, is continuously occurring feedback or complaints from occupants regarding indoor climate. It is similar to the previous category “control actions” by being driven by an urge on the occupant’s part to make a change, but differs by there being no immediate physical response to the user from a feedback event (Fig. 6). This information, for example, is used in the fields of participatory sensing or participatory

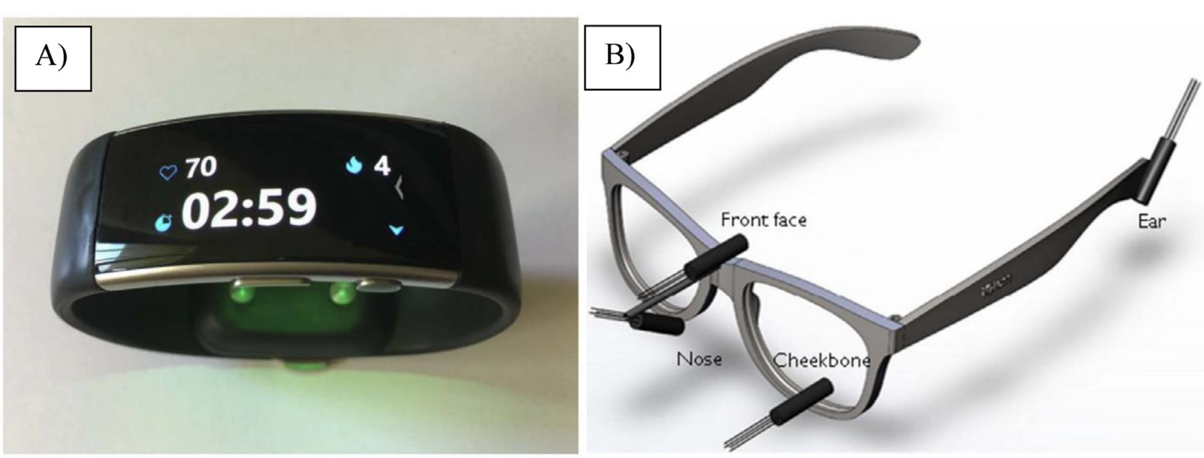

Fig. 4. A) Windows Band tracking heart rate, skin temperature, light intensity, activity level, sleep quality, etc. [51]. B) Prototype eyeglasses with infrared sensors for registering skin temperature in face [52].

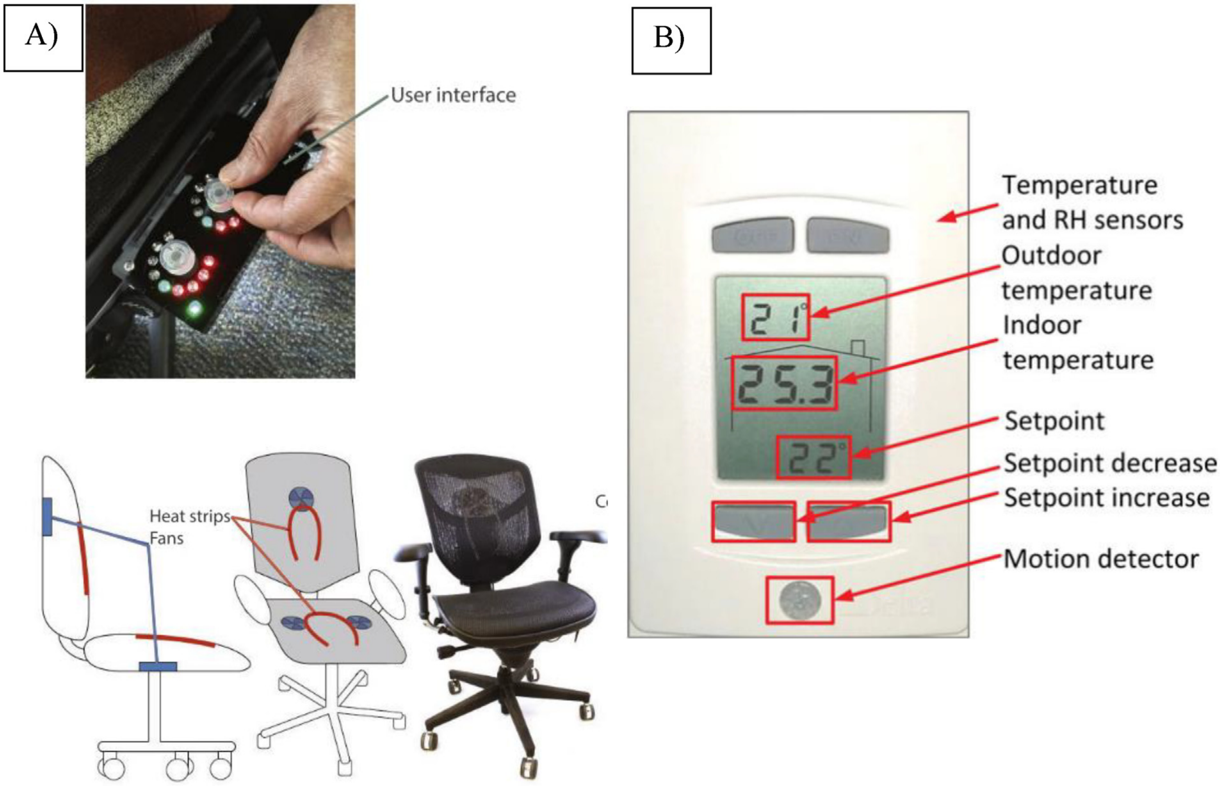

Fig. 5. A) Occupant controlled personal heating and cooling chair with internet connection [54]. B) Connected thermostat [55].

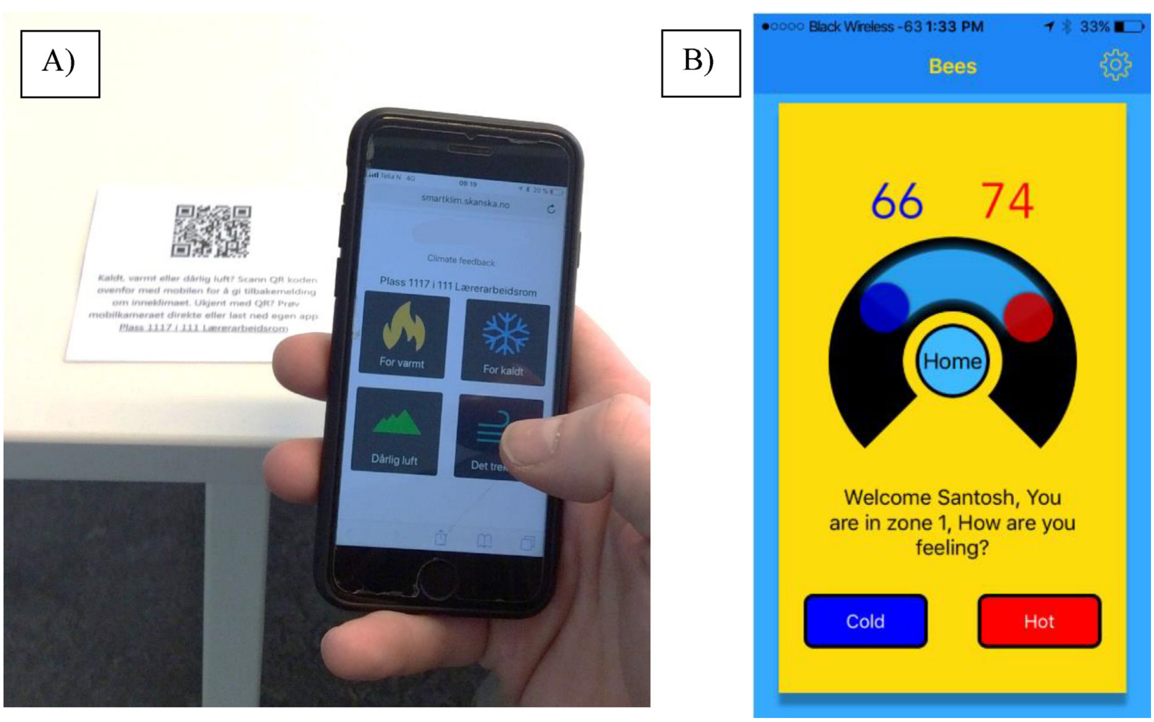

Fig. 6. A) Occupant complaint webpage interface accessed by QR code on workdesk [62] B) Smartphone app interface for real-time occupant feedback and environmental learning [59].

comfort control to let occupants control, in a democratic manner, the ambient temperature (which gives no immediate change) via the HVAC system using, for example, their smart phones. The key idea behind participatory sensing is to empower ordinary people to collect and share experiences from their surrounding environments using own devices or simple personal interfaces [56]. The individual differences in use of the subjective voting solution result in potential challenges related to fairness between occupants [57].

Even though participatory sensing and control solutions in theory are continuous data streams, they may in practice not be continuous for individual users if they do not make use of the solution on a regular basis. Several research studies have been conducted on the concepts of Participatory Voting and Participatory Control used in an indoor climate setting [58,59]. In addition, there are some commercial products available that utilize Participatory Control in office buildings [7]. Some systems have combined a Participatory Sensing or complaint feedback functionality with more operational or facility management related feedback, where occupants can use smartphones to report complaints or problems to facility operators [60,61].

2.2.5. Continuous occupant satisfaction evaluations and voting

Continuous occupant satisfaction surveys and voting represent a separated type of occupant data that builds upon the previous category. These are surveys or voting polls aimed at collecting voluntary evaluative responses from a representative number of users, and usually targeting the level of satisfaction that the occupant/user assesses (Fig. 7). Most often this is done through smartphone apps, smartwatch apps or by polling stations (fixed button or touch screen). They can be directed at the individual user (such as apps or personal polling stations), or at the public (as publicly accessible polling stations placed in an environment where the user passes by). Publicly located smiley-face polling stations have recently had a rapid growth for capturing customer satisfaction in airports, retail, public facilities and healthcare, and the survey responses are entered by single presses at smiley face buttons ranged from "Angry" via "Neutral" to "Happy", or similar types of scales. The concept relies on the low cost in time and effort for users to enter their response, resulting in higher response numbers. The concept has only been tested in a small number of research studies for application in indoor climate in buildings [63,64]. In a recent study we performed on the use of Satisfaction Polling Station (SPS), we identified a large risk of non-response biases as dissatisfied occupants tend to vote more often than those neutral or satisfied, making it difficult to directly compare data between buildings. Another method is to rely on scheduling or nudging techniques to make occupants submit their revaluations at regular time intervals. Designated apps for smartphones and smart watches have been developed and are commercially available for this use, which is more specifically directed toward research and short-term studies [45]. A particular aspect to consider in this type of occupant-centric data is that, contrary to other types, they require the establishment of scales that the occupants can use to convey the degree of satisfaction. As revealed by a recent study [65], significant differences may appear among the occupants in their perception of the scales adopted to convey the satisfaction, since the respondents' interpretations can change with contextual factors that are not only cultural, but may relate to the climate and the season.

2.2.6. Conclusive remarks on occupant-centric data streams

With the break-down presented in the previous sections, we have summarised how different types of data about the occupant can be collected. The grouping of the different categories of devices and data types presented has been carried out considering the hierarchical level structure of human physiological and psychological processes. We should mentioned that many of the systems shown in the literature combine several data streams in one solution, such as combining physiological data and subjective voting in a smartwatch app or similar systems [45]. The different nature of these occupant-data sources doesn't mean that they are mutually exclusive or incompatible, but it is important to stress that if a system targets more than one type, the embedded information in each type is different from that embedded in other types. Each type should, therefore, be addressed in relation to the cognitive processes associated to each of those categories, as we have clarified in the previous sections.

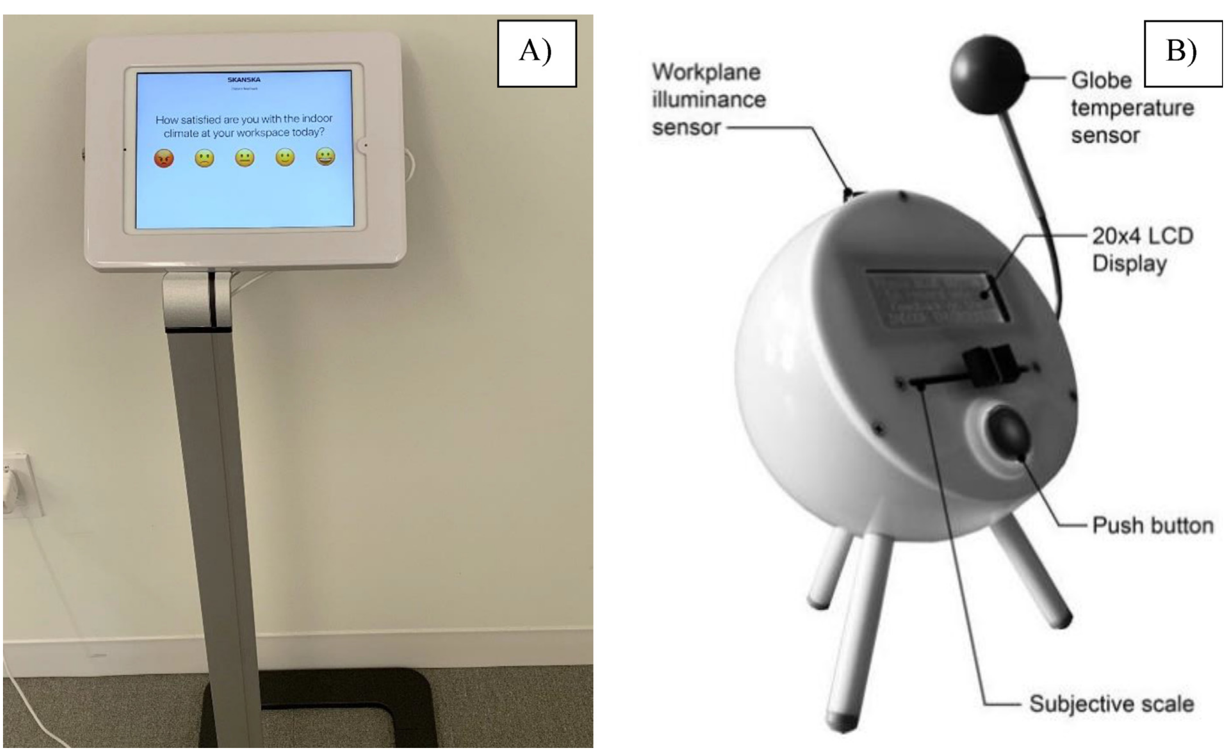

Fig. 7. A) Satisfaction Polling Station (SPS) [66] B) Desktop Polling station [67]

3. A conceptual framework for occupant-centric data-streams

As presented in Section 2, physiological and psychological aspects of human sensory processing can be divided in stages, from nerve impulses with raw data from the physical environment to the formation of verdicts about how the experience has fulfilled our prior expectations. We decided to use the different stages in the physiological and cognitive process as the backbone of the proposed framework for occupant-centric data. We believe that putting human physiological and psychological processes at the center of such a taxonomy is aligned with the aim of distinguishing the occupant-centric data types according to how the data can be understood, what information is carried with, and further utilized for benchmarking, learning, research, operation, or control applications. We understand the data as being enriched, or enhanced, with subjective, or individual, information for each step. While sensations and perceptions are raw information of the environment or the physiological reaction to it, cognitive data is seen to have a higher level of information as it involves personal cognitive processing and calculated choices. Evaluative information is at an even higher level, as it involves evaluations based on the summarized performance compared to a set of personal expectations and even emotions.

Based on this understanding, we define a framework articulated in 5 steps (Fig. 8), where the arrangement of the "levels" represents both the processing stage and the level of richness of the embedded information. The bottom level, Level 0, is called *"Activity and position*", reflecting physical data collected on the occupant-centric sphere such as presence, motion, clothing level estimation, etc. We consider this class as the entry-level data category, which is still outside the progression of physiological and psychological processes that constitute the main structure of the proposed framework, but clearly belonging to OCD. Level 1 has been called "*Sensation*" and reflects the subconscious and raw physiological reactions. At the best of our knowledge, data at Level 1, *Sensation* cannot be explicitly recorded as stand-alone data, as they mainly consist of coarsely processed nerve impulses in the brain stem. However, data derived from their post-processing can be collected at Level 2, which we have called "*Perception*". Continuing the progression of the hierarchical scheme, Level 3 has been called "*Cognition*", and the top Level 4 has been named "*Satisfaction*".

Each level (with the exception of Level 0, as previously explained) is characterized by a series of fundamental features of the embedded information that are linked to the physiological and psychological processes behind them, and can be schematized according to the following dichotomies: *physiological* vs. *psychological*; *conscious* vs. *subconscious*; *objective* vs. *subjective; reactive* vs. *evaluative*. These features are important when addressing the nature of the information collected in each level and to correctly align the expected meaning of the collected information with the actual attribute of the information. Common data sources identified in the previous sections are linked to the corresponding data level. The alignment between data source and embedded information, via the hierarchical level, is important to assure congruency between the tools and methods used to collect data and the expected embedded information. The framework is shown in Fig. 8, where data sources on the left are linked to information attributes on the right via the framework. The hierarchical structure of the framework is based both on the chronological and hierarchical stages of environmental information processing as well as on the level of subjective information richness present in each stage.

4. Discussions

We identify at least two domains where the proposed theoretical framework can be useful for classifying occupant-centric data: *design of systems for occupant centric control* (including also data acquisition for operation and benchmarking); and *research and development of models and theories for indoor climate*. The two suggested domains of applications are discussed below.

4.1. Design of systems

A system that collects occupant-centric data can be based, according to the organization developed in this taxonomy, on different levels, targeting different types of information. A system for occupant centric data collection can be intended for several purposes, such as real-time control, for assessing performance, or to collect data for model construction for linking interactions to operation of the building. Until now there has been little or no explicit reasoning regarding how the input, or collected data, is linked to the desired information feature for each use case. With this framework we believe that the design of these features can be more robust and more systematic. This in turn will improve the quality of research and performance of such applications. To show the functioning of the framework, we can exemplify two typ-

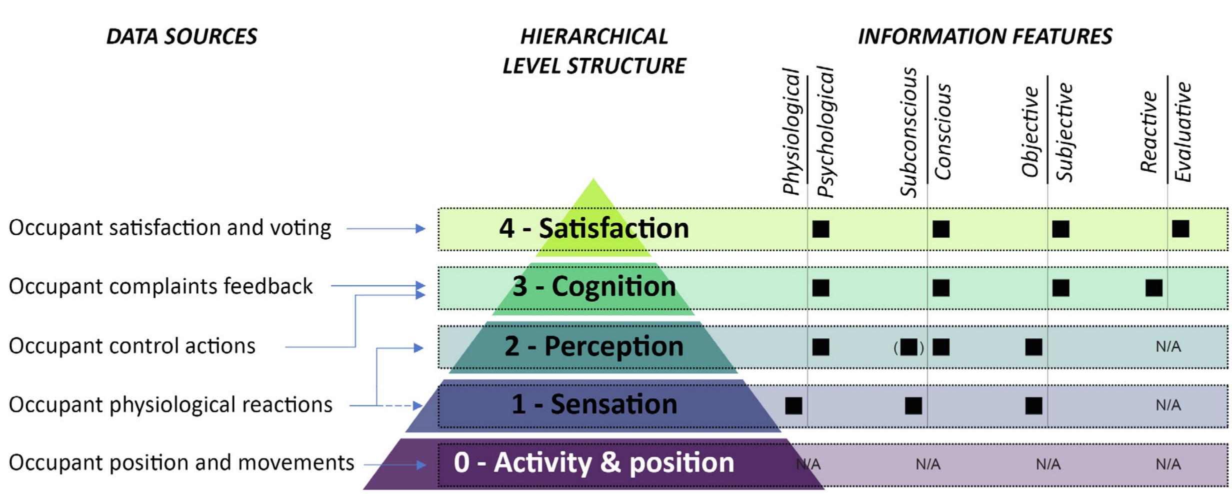

Fig. 8. Proposed framework for occupant-centric data streams. The framework is organized in 5 steps, reigning from Level 0 (Activity & position) to the highest Level 4 (Sensation). Each level is characterized by features derived from physiological and psychological processes. Different data sources, as presented in Section 2.2, are linked to the different steps in the hierarchical level structure and thus connected to the different attributes for the information embedded in each level.

ical processes that can be supported through the use of the framework. When data are collected, for instance, though a *continuous complaint feedback system*, the framework allows to easily and immediately classify the data type as *Cognition*, and highlight the nature of this information as psychological, conscious, and subjective. The knowledge and awareness of the specific nature of the collected information is crucial for the correct understanding of how we can make value of the new data, as well as for which purposes it is not suited. An example of the opposite process is, instead, setting the goal of collecting information that is conscious and subjective (for example for assessing the performance of a holistic design solution), and observing through the framework that this type of information can be achieved by either collecting data at the *Satisfaction*, or in some cases *Cognition,* level. This can perhaps be done with a polling station by asking users to rate a feature.

5. Research and model development

The proposed framework can also be useful, in more general terms, for the design and communication of research and for more fundamental investigations related to theories and models in indoor climate. For example, it is seen in the field of thermal comfort that several scales for collecting responses from subjects (in laboratory or field experiments) contain elements of both cognition and evaluation in the same scale [20]. This happens, for example, in the scale known as the "Bedford scale", characterized by the markers COLD – COOL – COMFORTABLE COOL – COMFORTABLE – COMFORTABLE WARM – WARM – HOT. In light of the framework we propose in this paper, such a scale mixes information from two different levels characterized by different information attributes. This exemplifies that a better understanding of how subjective rating scales are linked to human psychology is crucial to correctly interpret the embedded information in research results. Although this issue has also been identified by other researchers, it has in our eyes not yet been given the attention which is needed in the research community. This importance of this issue is made even clearer as we further develop our data collection methods to involve automated, continuous, and even non-intrusive collection of occupant feedback in research.

The taxonomy we proposed for classifying occupant data, and especially its backbone based on a clear hierarchy of physiological and psychological processes as defined in different fields of psychology, can be adopted as a possible key to evaluate and develop correlations and calculation models that attempt to predict the occupant's experience of thermal comfort conditions. The taxonomy can be particularly useful to help researchers ensure that the collected environmental, sensory, or cognitive information is aligned with the desired purpose of the model or metrics under development. An analysis of how current models and methods are built up and carried out is possible (and relatively simple) though a repeated application of our framework.

For example, the classic deterministic models of thermal comfort research, as stated in the comfort equation and the adaptive comfort model in ASHRAE 55 and in ISO 7730, aim to predict thermal sensation (Predicted Mean Vote, PMV) and thermal comfort (Predicted Percentage Dissatisfied, PPD) based on input of the thermal environment. The adaptive comfort model acknowledges the effect of expectations by also incorporating the outside conditions. PMV clearly contains a cognitive evaluation of the perception of warmth (thermal sensation), while PPD refers to a cognitive and affective evaluation of acceptability or (dis-) satisfaction. These models are deterministic models predicting at level 3 and 4 from measurements from the physical environment at level 0, thus predicting 3–4 levels upward, without any additional information collected from the higher physiological or psychological levels. Lately, more advanced models which predict occupant thermal sensation from physical reactions such as skin temperature, heart rate, electrodermal activity etc. have become increasingly popular. These models combine input data from environmental monitoring with higher level physiological and psychological input data from Level 1 and 2 to determine a thermal sensation verdict at Level 3, thus predicting 1–2 levels upward. We see, based on the framework, how the models attempt to predict the subjective opinions of occupants at a conscious level (3–4), from objective information at unconscious levels (0, 1, 2). This is, after all, the intent of a model, but the presented framework allows us to closer dwell upon the nature of the output information as opposed to the nature of the input data, and perhaps avoid making unrealistic assumptions and predictions. Common examples of such unrealistic assumptions are the assumption of equidistance between thermal sensation votes (which are highly subjective and interpreted differently by users) and the assumption of a direct relationship between the PMV and PPD metrics (all present in the classical comfort models) [20]. This view also highlights the obvious difference between model predictions and real-time control based on occupant feedback. Indoor climate research has typically been focused at creating models. We think that the awareness of the hierarchical nature of subjective data can contribute to appreciating the value of direct subjective feedback and control in a time where these measurements are being made feasible through new technology.

If the goal is for occupants to experience thermal comfort, this can, according to existing literature and standards, be targeted by reducing the number of occupants who are thermally uncomfortable at Level 2–3. If the aim is to have thermally satisfied occupants (according to a "consumer of indoor climate" view of occupants), this must be targeted by maximizing the reported satisfaction with thermal conditions, measured at Level 4. When this is classified as a higher order psychological process, it is clear that it is also affected to a larger degree by other psychological aspects such as expectations, culture, etc. and the relationship between the Level 4 information and the physical thermal conditions can to a larger degree be expected to be influenced by psychological factors. The distinction between these levels has in our opinion not been sufficiently highlighted in thermal comfort research to this date, and we believe that a taxonomy to emphasize the differences can contribute to making both research and occupant centric data collection and utilization clearer in the future.

6. Conclusion

Occupant-centric data is an emerging field that reflects the newly understood importance of collecting information from the occupants themselves to be able to predict their experience with the indoor climate. This is crucial for operating buildings in a way that promotes the occupant's wellbeing. Various types of data can be collected from the occupants using modern technology. This data contains varying intelligence, which should be aligned with the scope and use foreseen for that particular information.

Based on well-established theories in different domains of psychology, we have built up a conceptual framework that attempts to organize the diverse nature of occupant data according to a hierarchy that addresses stages in the human process of interpreting environmental information. We defined a multi-level structure where five different levels (namely, *Activity & position*, *Sensation*, *Perception*, *Cognition*, and *Satisfaction*) are presented and their relations explained. We also highlighted four basic information features for each level that clarifies important characteristics of the embedded information: *physiological* vs. *psychological, subconscious* vs. *conscious, and objective* vs. *subjective, reactive* vs. *evaluative*. The work mainly refers to examples in the thermal comfort domain, but we see no relevant reasons for preventing it from being applicable for other indoor climate domains.

The proposed taxonomy is intended as an initial, open-to-development, attempt to provide the scientific community with a robust and comprehensive framework that can be used as a vocabulary for communicating and addressing important issues during research and collaboration, as a practical tool for designing data collection systems, or as a tool for research and model development. Hopefully it can promote a better understanding across different domains of indoor climate and foster a more multidisciplinary development of future systems, models, and theories.

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.

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