A review of comfort, health, and energy use

Understanding daily energy use and wellbeing for the development of a new approach to study comfort

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Review

A review of comfort, health, and energy use: Understanding daily energy use and wellbeing for the development of a new approach to study comfort

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ABSTRACT

There is a need for reducing dwellings' energy consumption while maintaining a comfortable and healthy indoor environment. This review was performed to provide a steppingstone for identifying new methods for studying everyday home energy use and comfort. First, an overview of comfort is given as seen from different disciplines, depicting the subjective and multidimensional nature of comfort. This is followed by the biological component of comfort, reflected as an emotional, behavioural, and physiological reaction to environmental stimuli. Subsequently, links between comfort, health, and wellbeing are introduced. The second part of the review focuses on energy and buildings, with the connection between energy and behaviours-detailing possible explanations of performance gaps, and the pathways from energy to health.

To conclude, human sensation of comfort is more complex than the perception of thermal, acoustical, visual stimuli, or air quality environment. Comfort is a reaction to the environment that is strongly influenced by cognitive and behavioural processes. Habits and controllability have been identified as paramount in the links between comfort and energy consumption. In this holistic view of comfort linked to health, comfort is referred to as 'wellbeing'. The first steps for new directions of the study of comfort and energy are presented.

Contents

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1. Introduction

Comfort has traditionally been studied from the perspective of the physics of the environment and the physiology of the occupant, in terms of four factors: thermal comfort, acoustical quality, air quality, and visual quality. Codes and standards for each of the factors have been established, and technologies and systems are being engineered in order to satisfy such standards in a presumably energy efficient manner. The challenge with such an approach is that individual standards for each of the factors are not meant to be used as human's global experience of comfort, which causes challenges and risks [1].

Additionally, there is a need to provide energy efficient buildings that are also healthy; which is not always the case [2]. Occupant behaviours seem to be responsible for the discrepancies between actual and theoretical energy consumption (i.e. rebound effects, performances gaps) [3]. As a result, it was found necessary to perform a literature study on the links between energy use, comfort-making, and health, in order to identify a potential new approach in the study of the interactions between those topics.

2. Materials and methods

An extensive literature review was performed in the topics of health, comfort, and energy use, with a focus on the interactions between the occupant and the environment. Three topics form the focus of this literature review: the first being comfort as a cognitive-behavioural process, specifically reflected with the concepts of sense of control, habits, and emotions. The second topic deals with energy in buildings: first providing the current consumption trends in the Netherlands – chosen as a country – specific case-study –, followed by a discussion on the rebound effect and performance gaps; the third, discussing human factors in terms of energy habits and the relation with health.

The aim of this paper is to provide better understanding of the several factors influencing energy usage, from a perspective of the psychological and behavioural interactions of the occupant and its environment. Many of these interactions – whether conscious or unconscious – are performed to achieve homeostasis (i.e. comfort, neutral state, less discomfort, etc.). These behaviours are here referred to as 'comfort-making activities', and have been specifically identified as controlling the environment and habitual actions – actions that enable psychosocial homeostasis. By understanding the energy use through this approach, it is intended to set forward a conceptual framework for the research of energy use.

The review was performed by searching in engines such as Google Scholar, ScienceDirect, and Web of Science. The selection of the literature was limited to articles from peer-reviewed journals and conference proceedings. For the health section, a table was made in which the articles are categorized according to their strength of evidence. Data from academically published books and Dutch websites of energy and economic affairs were also included. Because of the interdisciplinary nature of the review, in order to find the same topic but in different fields, the field in question was added in the search in quotation marks (i.e. "nursing", "psychology"). The different tags used for the research fields are shown in the following table:

Term (construct)		AND / OR	Term (location)	AND / OR	Discipline	
Behavior			Domestic		Environmental	Psychology
Comfort			Residential		Sociology	
			Home		Nursing	
Emotions			House		Indoor environmental quality	
Energy	Use		Housing		Ergonomics	
	Consumption		Environment		Design	
	Expenditure					
Wellbeing			Dwelling		Healthcare	
Habits					Holistic	
Controllability					Evolutionary biology	
Homeostasis					Human centered	Design
					User centered	
					Emotional	

The collection of information was used to illustrate the current situation in the domains of health and comfort in the built environment and the relationship with energy use from a multidisciplinary perspective. By being acquainted with the current situation, intervention points were identified for the study of comfort and energy, in order to suggest a possible new approach for the understanding of residential comfort and energy expenditure.

3. Results

3.1. Comfort

3.1.1. Comfort definitions by discipline

Due to the subjective nature of comfort, individual fields that need to investigate comfort have developed their own definitions of the concept. To gain a multidisciplinary and comprehensive understanding of what comfort is, the definitions on the fields of IEQ, healthcare, and ergonomics are presented, along with a 'domestic' and a holistic definition which have been put forth.

3.1.1.1. IEQ. In the IEQ literature, comfort is viewed from a physiological-technological perspective and described through the following parameters: visual (with aspects such as view, illuminance, and reflection), thermal (air velocity, humidity, and temperature), acoustical (control of unwanted noise, vibrations, and reverberations), and air quality (smells, irritants, outdoor air, and ventilation) [4]. There exist international and country-specific

standards (for a few chemical substances) and guidelines are available for IEQ factors. Energy consuming systems and products are developed so that they can contribute to achieve the standards or guidelines. For thermal comfort, the adaptive approach has been proposed; comprising a model for studying thermal comfort through the adaptive principle: "*if a change occurs such as to produce discomfort, people react in ways that tend to restore their comfort*." This is achieved through "adaptive actions" enabled by "adaptive opportunities" [5,6].

3.1.1.2. Healthcare. In the healthcare literature, comfort is defined as a concept of two dimensions [7]. The first dimension consists of three states: 'relief', 'ease', and 'transcendence', which have to be experienced by a patient to be comfortable. Relief is the feeling of having had specific needs met, ease is the state of calm and contentment, and transcendence refers to the state where the patient goes beyond problems or pain. The second dimension of comfort deals with the context where comfort happens. The context can be physical – relating to bodily feelings –, it can be psychospiritual – relating to the inner self-, it can be social – relating to family or cultural relationships, or it can be environmental – dealing with light, noise, temperatures, sensations [7].

3.1.1.3. Ergonomics. Due to the wide scope of the domain of ergonomics, several definitions exist. A general definition is that when a product is comfortable, performance increases: comfort is "*an ease and contentment with the environment or product that facilitates performance*" [8]. The literature of ergonomics and comfort is dominated by seating comfort. For chair ergonomics, comfort is defined with factors related to "aesthetics and plushness, relaxation, well-being, and relief and energy" [9].

3.1.1.4. Holistic. Some authors have put forth integrative definitions of comfort which also include a cognitive dimension; for example Slater has proposed "*a pleasant state of physiological, psychological and physical harmony between a human being and its environment*" [10]. De Looze et al. [11] have identified that in comfort definitions across disciplines, three elements are certain and recurring: 1- comfort is a construct of a subjectively defined personal nature; 2- it is affected by factors of a various nature (physical, physiological, psychological); and 3- it is a reaction to the environment.

3.1.1.5. Domestic:. Heijs and Stringer [12] have also proposed specific elements of comfort in the domestic context, implying the place of residence. These are perceptual, interactive, facilitative, and personalization comfort [12]. These elements are related to contextual affordances that enable the occupant to carry out the behaviours according to their social and personal needs and to give meaning to the place through emotional attachment and self-identification.

For a general overview of the scope of environmental factors and human factors covered by comfort in different domains, refer to Appendix A, Table A1: *Scope of comfort by discipline and by human and environmental factors*.

3.1.2. Evolutionary biology, emotions, and behaviour

To show the link between comfort and energy consumptions, in this section, the biological origins of comfort are presented, along with the relationship between the comfort and emotions, and that of emotions and behaviours.

3.1.2.1. Evolutionary biology. Humans are the result of a several million year evolutionary process in the East African savanna. Therefore, there are still physiological, cognitive, and behavioural legacies of the evolution present in modern human. The physiological characteristics of humans reflect its evolution in the savanna; an environment with rainfalls, grasslands and forest mix, mild variating temperatures, and predators. The transition from the savanna lifestyle to today's environment occurred in an evolutionarily too brief of a period for changes to occur, rendering modern humans physiologically and psychologically identical to their first human ancestors [13]. As a result, humans are in many respects maladapted to their environment. In spite of not having any modern technologies, early humans dispersed around the globe and managed to live from polar to desert regions, due to two basic strategies: appropriate clothing – the second skin – and appropriate shelter – the third skin. These extra skins have allowed compensating for and adapting to the more extreme climatic conditions and still achieving acceptable conditions [13,14].

3.1.2.2. Emotions. One of the results of evolution are emotions. Emotions are specific states that increase the adaptability and ability of a person to cope with a specific situation, which may be a threat or a benefit to their wellbeing. One model that explains emotion elicitation is the three-level processing model [1,15]. The model explains that the feeling of an emotion emerges from three reactions: reactive, routine, and reflective; each of which is elicited by different aspects of the environmental stimulus. The reactive reaction deals with immediately perceptible sensory characteristics of the stimulus: appearances. This is a biology-driven reaction, in which reasoning does not happen: it allows to unconsciously assessing the stimulus as a threat or a benefit. The routine reaction involves automatisms, such as habits, from long-term memory and expectations during active interaction with the stimulus: the predictability of the performance and usage. Finally, the reflective level involves the fully-felt emotion: the conscious appraisal and rationalization of what the stimulus and event means to the person, in terms of relatedness to the values, beliefs, and needs of the person [1].

3.1.2.3. Behaviours. Emotions are tightly linked to behaviours and decision-making. Feeling emotions enables making decisions and motivating behaviours. It has been shown that people with lesions affecting their emotional system are unable to make decisions or behave accordingly, in spite of being psychologically and behaviourally normal in every other aspect [16,17]. Some types of behaviours are controlling the environment (controllability) and exercising habitual actions (habits).

Habits are part of the routine level of response, and are defined as "learned sequences of acts that have become an automatic response to specific cues and are functional in obtaining certain goal or end states" [18]. They are the result of associative learning from environmental or contextual cues and of responding to such cues through procedural memory. Thus, habits are a type of behaviour that is unconscious and automatic, and that are repeated when a particular stimulus is perceived [19]. Habits are formed by the initial motivation to achieve a goal within a context and with cues. With repetition, perceiving the cue elicits automatically the behavioural response to mind, which is normally performed. Further repeating the habit strengthens it, and even when the original goal or reward is not needed, habits will still be triggered by the contextual cues. This occurs since carrying out a habit activates the dopamine systems, reducing cortisol, which as a result strengthens the habits further, due to the experienced pleasure. Thus, performing a habit only by itself produces feelings of pleasure. In addition, habits allow the individual to achieve goals in a quick and effective way that requires minimal thought [19–21]. Many elements of habits overlap with those of comfort, such as elimination of negative affect, reduction of the stress hormone, and controllability of the environment. Repetitive, stable, and predictable environmental

cues that elicit habits also indicate the degree of feeling in control over environment.

Controllability encompasses the concepts of "perceived" control and "actual" control; perceived control being the level of control a person believes to have, while the actual control is the behavioural exertion of control by the individual. Controllability evolved from the need of protection against predators. In evolutionary terms, shadows, movements, shapes that could be a threat to the human's life were uncontrollable and caused a fight-or-flight response [13]. To this day stimuli reminiscent of threats still elicit the chain of hormonal reactions, culminating in the fight-or-flight response. This response makes the human ready to fight against the threat or flee from it, which would typically last from a few seconds to minutes, and then the physiology and hormones would go back to a normal state. In the modern lifestyle, many ordinary stimuli associated with not feeling in control, still trigger the fight-or-flight response, however, in most cases, the person cannot rationally flee or fight the modern stressor (i.e. locked windows, neighbours, debts, leaks, etc.) [13]. Thus, the stressor becomes a 'constant threat', and as a result, the hormonal and immune systems come out of balance due to chronic stress (allostatic load). Studies have shown that there is an association between the lack of sense of control and diverse stress-related health problems, such as depression, anxiety, high blood pressure, and weakened immune functioning [22]. The feeling of being in control not only reduces stress-related health issues, it also increases the feeling of comfort, it makes people feel more satisfied, and in the workspace, workers feel more appreciated. Choices offered by the environment (i.e. operability of windows, decorating, privacy and social interaction, cooking, etc.) afford the occupant to have a feeling of being in control. The need for control and choice are closely related. The presence of environmental choices enables a person to exercise control or to increase their perception of control over their environment, through behaviours that avoid undesirable results or through those that achieve desirable ones [23]. Thus, when a person has choices and is able to decide, they may feel less stressed and more comfortable [24–27].

3.1.3. Environment and health

This section deals with the existing evidence of environmental influences in mental health, particularly from the perspective of psychoneuroimmunology (PNI). One of the proposed pathways in which the environment influences mental and physical health is through the emotional responses the environment elicits in the occupant. In their turn, the emotions influence mental and physical health, as explained in the section. The first part, 'From Environment to Emotions', deals with the current evidence as to how the environment influences emotions. Examples in healthcare and office settings are provided, since research in the residential context is lacking. The second part, 'From Emotions to Health', shows the next part of the aforementioned process between "environment-emotions-health". It presents the biological processes that occur when positive emotions are present and their effects on mental and physical health.

The environment provides stimuli that elicit an emotional response in the person, which helps the person to cope with the situation. Therefore, environments have the potential of causing stress, but they can also have restorative effects, influencing well-being [28–30]. PNI studies the interactions between health, mind, and environment, with the focus on the influence of psychological and social factors on human physiology, and thus, it examines the links between the environment, brain, behaviour, and the immune system [31].

3.1.3.1. From environment to emotions. Most of the evidence linking environment to health and wellbeing comes from environmental psychology studies, healthcare environment design, and sick building syndrome research. The evidence in such studies is based on the prevalence of physiological symptoms, evidence of positive health outcomes, nature restoration theory, cortisol levels, depression, immune regulation, and attention restoration theory [32–38]. Healthcare design aims at making patients feel better to heal faster by reducing stress and increasing comfort, via environmental features, while in the office setting, productivity, creativity, and physical and mental health are the target to improve. In such studies it is shown that environmental aspects have an effect on the mood of patients, workers.

3.1.3.2. From emotions to health. There is not only a link between environmental cues and emotions, but also one between emotions and health [39]. Evidence indicates that positive emotions have an influence on both health and longevity [40]. Positive emotions have been associated with lower blood pressure levels, as well as reduced inflammatory processes and neuroendocrine, cardiovascular and immune strengthening, while negative emotions can cause stress, anxiety, depression, and eventually damaging changes in the cardiovascular system [41–44]. Similarly, negative moods contribute to delayed healing from wound and infection, while it has been documented that angry people have weaker immune responses to vaccines, as opposed to optimists. Likewise, the prevalence of self-reported rhinitis has been found to be higher amongst students with recent negative life events [45]. One of the pathways from emotions to health occurs since negative emotions stimulate the production of pro-inflammatory cytokines, which lead to inflammation. In its turn, inflammation unbalances hormonal production and damages the healthy reproduction of cells, linking this with cancers and a variety of diseases [46].

Therefore, humans react to stimuli in their environment. This reaction is first emotional, then behavioural. The emotion guides the behaviour – negative emotions (stress/discomfort/displeasure) will trigger behaviours whose purpose is to eliminate or reduce the negative stimulus of the environment. The behaviour – either through control or habit- serves as a tool to bring homeostasis: to reduce the stress (discomfort/unbalance) caused by the environment, and to bring the individual's state back to a neutral one (comfort/lack of discomfort).Finally, the aforementioned studies suggest the strong connection between the environment, human emotions, behaviours, and health. However, these types of studies are predominantly done in the office and hospital contexts, leaving a knowledge gap regarding the domestic context.

3.2. Energy in buildings

Traditionally, energy technologies and occupants' behaviour have been treated as separate actors in the domains of indoor environment, energy engineering, and social fields [47]: in spite of more recent efforts to link them, by viewing energy consumption as something performed by individual rather than solely technologies, in a context of interrelationships between users, technologies, skills, social contexts. In the engineering fields, the focus is on the development of efficient technologies – reducing greenhouse gases, reducing cost, etc. [50,51]. In the social fields, the focus is on behavioural changes through campaigns, awareness, and information [48,49]. As a result, on the one hand, governments and energy policies carry out campaigns with fines, public information, etc., to try to stimulate householders' behavioural changes. On the other hand, the building and technology industry strives to produce more airtight houses, more stable temperatures, and less energy-consuming technologies [52–55]. The fact that the two domains work independently to achieve lower energy use, could be the underlying reason leading to discrepancies observed between actual and theoretical energy consumption.

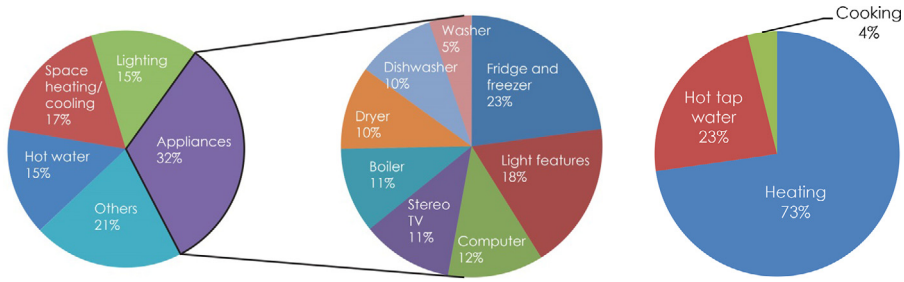

Fig. 1. Dutch electricity consumption and appliance breakdown and Gas consumption (adapted from milieucentraal [57] and Majcen [56]).

3.2.1. Energy and behaviours

3.2.1.1. Theoretical vs. actual consumption. While theoretical energy consumption calculations tend to ignore the part of the energy expenditure determined by the occupant's lifestyle (behavioural determinants), actual energy consumption is obtained from final energy bills and meters of the household building in question, reflecting the consumption of every single appliance and behaviour. In 2002 in Europe, the European Performance of Buildings Directive was passed, introducing the Energy Performance Certification (EPC) labeling for residential buildings. The EPC model is calculated according to a methodology that considers insulation, heating, hot water and ventilations systems, and fuels used; therefore ignoring appliance use and human behaviour [56]. The difference between the predicted consumption and the actual one is called "performance gap". In a study performed by Majcen as shown in Fig. 1, for electricity consumption, electric appliances are an ignored variable when making theoretical calculations. According to milieucentraal.nl, in the Netherlands, such appliances represent about 32.4% of the household's total electricity consumption [57]. While for gas usage, the main ignored variable in theoretical estimations is 'cooking behaviours'. From the total energy consumption of a Dutch household, on average gas accounts for 67.3% of the total actual energy consumption, while electricity accounts for 32.7% [56,57].

In the 1980s it was estimated that human factors, such as attitudes of residents towards energy based on prices, environmental concerns, health concerns, and comfort, could influence up to 5% of the variation of consumption [58]. Recently, at international level, the IEA identified three major causes of performance gaps: climate factors, building factors, and human [3] behaviour. Different studies performed in EPC labelled dwellings have shown that occupant behaviour heavily influences energy consumption, and it has been shown that actual energy consumption is in every case higher than the predicted one [59–61]. Such behavioural determinants of consumption are interactions with services and technologies, as motivated by occupancy patterns, attitudes, and beliefs; all of which are correlated with the occupant's behaviours. The fact that such variables are not considered in estimations is likely due to the fact that the engineering and design process of buildings, systems, and technologies (from micro to macro scales, i.e.: knobs, buttons, interfaces, layout, spaces, automations, services, etc.) also tends to exclude such human factors: users' needs have to be understood by involving the user in the process [4,62–65]. Yao and Steemers [66] propose that occupancy patterns (number of occupants, sleep and wake times, and daily occupancy time) influence energy consumption. These patterns influence both physical and behavioural determinants of consumption. Physical determinants are factors such as heating, cooling, lighting, determined by characteristics such as dwelling size, design, systems, services, and climate, while behavioural determinants are factors such as frequency of use of appliances, systems [66].

Similarly, the social practice theory contends that the centre of energy consumption is guided by social dynamics as ordered in time [67,68]. In other words, certain social practices are performed at specific times, and the fact of carrying them out, as a society, brings energy demand to a peak in a certain place. Social practices can be habits such as working, cooking, washing, or watching TV, each of which is generally performed at specific times in similar societies. Therefore, it is advocated that to understand energy consumption, it is indispensable to understand such social practices and their timing [68].

3.2.1.2. Energy and wellbeing. The relationships between energy and wellbeing are complex and involve many variables. However, generally by Western standards a 'good life' at home tends to translate into higher energy usage [69]. One of the links between wellbeing and energy use in households is related to standard of living and quality of life: several energy-consuming activities improve wellbeing, such as maintaining liveable temperatures, refrigerating perishables, cooking, hot water access, lighting, and other technologies that bring convenience to occupants [70]. It has been estimated that in less than one generation, expectations of comfort via central heating and air conditioning have become a norm [71]. However, it has been proposed that energy savings can be achieved while still maintaining a high quality of life and wellbeing provided by the energy consuming services.

3.2.1.3. Energy and habits. Recent findings show that most of everyday behaviours are guided by habits, especially when interacting with technology since technology acts as a contextual cue that triggers the habit [72–74]. In the residential context replenished with energy appliances, it is assumed that it is more probable that humans will use "simple heuristics" or habits; since it is an environment with cues that do not require cognitive effort [74,75]. Another reason why habits are strong in the domestic context, is because, 'home' provides cues that are physical, social, and temporal, all of which enable habit creation and strengthening [76]. Additionally, as in most cases, energy consumption is 'invisible' for the occupant, which strengthens possible unsustainable habits [77]. These habitual interactions occur with appliances but also with interfaces of systems – thermostats, lights, equipment, etc. – and those of the building envelope – windows, shades.

Because of the unconscious and automatic nature of habits, they have been shown to prevent a willing person to change into pro-environmental or more efficient behaviours, and thus, habits could make people act in ways that are opposite to their intentions [77], without noticing [21,71]. Finally, because of their unconsciousness, habits have been either overlooked or understudied in energy consumption research [21]. Furthermore, in order to change habits into more sustainable ones, it is suggested that policies should tackle the tangible environmental cues that trigger the habits themselves [76,78]. This is because the environmental characteristics have higher impact on energy consumption than other variables, such as attitudinal ones [79].

3.2.2. Health and energy

The study of the relationships between home energy and health is complex, since there are several linking pathways, measurement of exposures, dosages, long term effects, as well as the multiple interacting, dynamic, and interdependent building and occupant factors [80–85]. As a result, there is still debate about the impacts on health of energy efficient homes. There is evidence that energy efficient homes, measures, or interventions modestly improve some aspects of physical health of occupants [86–90]. Although research has been done on the effects of climate change and outdoor temperature on certain populations, this review focuses solely on the indoor environment and temperatures. It has been reviewed that thermal comfort improvements in homes seem to generate health improvements, specifically in those who suffer chronic respiratory diseases. In a similar vein, households capable of heating their homes are also linked to better health and social relationships, and lower school absenteeism [91]. The limitations of such studies are that they focus on start- and endpoints without considering the network of factors, causes, and effects [39]. For a full overview of those studies, refer to Appendix A, Table A2. Effects of energy efficient measures on health of occupants.

Airtightness has been encouraged by the European commission in order to satisfy energy standards. However, with airtightness, the indoor air quality of the dwelling could be at risk. High airtightness needs adequate ventilation rates and system maintenance. Inadequate ventilation in an airtight home can lead to increased dampness and humidity, and thus higher concentrations of biological, chemical, and physical contaminants (CO, NO_2, CO_2, formaldehyde, VOCs, radon, PMs, mites, moulds, etc.). These pollutants have been associated with several health risks, especially with the prevalence of respiratory and allergic effects both in children and adults [39,89,92–94]. Nevertheless, airtight buildings with properly maintained mechanical ventilation systems, especially for its efficiency in filtering ambient particles, could offer modest improvements in symptoms or health outcomes [95,96]. In the HOPE project it was found that there is a correlation between perceived comfort variables themselves, and between Building Symptom Index variables and comfort variables; suggesting that energy-efficient buildings with good indoor environmental quality and healthy occupants are possible, but the opposite also exists [2,97]. In the European Audit project, it was concluded that to improve indoor air quality without consuming more energy, source control should be applied to materials, systems, and polluting activities; thus, reducing pollutants while maintaining low ventilation rates [98].

4. Discussion and findings

4.1. Narrow view of comfort

In attempting to follow 'standards', the IEQ perspective of comfort tends to fall short when unavoidably combined with the standards required for energy efficiency, due to being limited to single parameters of the four IEQ factors (air quality, thermal, acoustical, visual) ignoring possible interactions as well as differences among people. The literature review shows that comfort is a wider and deeper phenomenon of subjective nature and contextual dynamism. Taking this into account, in this review, it may be better to refer to it as 'wellbeing'. This is because – as mentioned earlier- comfort-making activities are equivalent to the attainment of homeostasis, and thus imply the reduction of stress and consequently, the improvement of health. Holistic and domestic comfort definitions have also been put forward. Comfort is more than a physiological reaction; it is a subjective reaction to environmental stimuli, which can be behavioural, social, physiological, psychological, and physical, and that indicates harmony and neutrality with the stimuli.

These further dimensions of comfort are missing from the IEQ perspective. In IEQ it seems that the current definition does not provide enough knowledge about comfort's behavioural quality: a crucial aspect when studying energy use. Although an adaptive model for thermal quality exists, in-depth analyses of the proposed "adaptive actions" seem to be lacking and are restricted to five types of actions: heat generation and loss (physiologically), regulating the thermal environment, selecting a different thermal environment, or modifying the body's physiological comfort conditions (moving, adjust layers, etc.) [5]. As a result, this model falls short both in depth and broadness, being confined to thermal comfort and to the aforementioned types, while ignoring the investigation of the actual "adaptive activities" and "adaptive choices".

From the literature review four main points can be concluded: firstly, generally humans avoid discomfort and unpleasant experiences, and hence they are always striving (whether consciously or unconsciously) to change their present state towards a homeostatic state – thus a more neutral or comfortable one. As a result, many of the actions we do are wellbeing-driven: actions that can have effects on both health and comfort. Secondly, household energy consuming technologies are tools that allow occupants to achieve such comfort and wellbeing by performing the activities. Thirdly, energy consumption occurs when occupants interact with such technologies when they search for 'wellbeing'. Fourthly, habits and control actions are types of behaviours that particularly consume energy, and they are, to an extent and amongst other factors, influenced by the person's (energy) attitudes and emotions. These attitudes towards energy vary from person to person, and hence, behaviours are different amongst different people, while personal differences of comfort perceptions and thresholds exist. As a result, there is a need to understand energy consumption from a behavioural perspective, in relation to the 'wellbeing' motivations of such behaviours.

4.2. Gaps in knowledge

Humans experience their environment via many mechanisms, including the simplified sequence of 'senses-emotions-behaviours'. Behaviours enable the individual to change their current emotional state: a negative affect will motivate behaviour to change something in their environment and a positive one will motivate them to encourage their current behaviour. The behaviours that are pertinent to wellbeing and energy are sense of control and habits, in that, in the home environment, they tend to have as a secondary effect of the expenditure of energy. Moreover, the fact of exercising control and carrying out habitual routines is in and of itself stress relieving; affecting thus both the short term feeling of comfort and the long term health.

Habits have been identified as the primary cause of performance gaps; however, they have seldom been studied due to their unconsciousness and automaticity. Nevertheless, in order to reduce energy consumption, the IEQ and energy engineering fields would need to investigate such types of behaviour within the context of 'comfort' so that technologies are designed by considering occupants needs. Sense of control is another type of behaviour of relevance to wellbeing and energy; since being in control means to give choices to the user, choices that generally will influence the final energy output.

5. New directions

In this review, evidence suggests the need for a new approach in the study of comfort and energy consumption. "Comfort" is a mul-

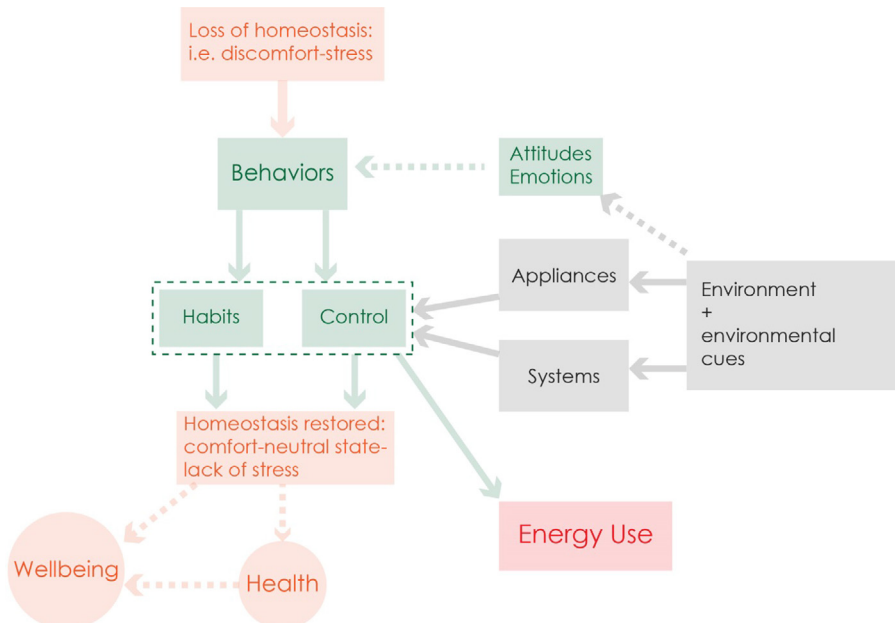

Fig. 2. Conceptual Model: Loss of homeostasis (discomfort, distress) triggers the occupant to find again a more neutral state (i.e. comfort). This is performed by manipulating their environment (via interaction with appliances, systems) through behaviours (habits or control). Behaviors are to an extent guided by emotions and attitudes. Finally, when homeostasis is achieved, health and wellbeing are achieved in the long term. The interaction with the environment results in energy use.

tidimensional and subjective construct that varies across contexts; however, by looking at it from a biological perspective, comfort is the maintenance of homeostasis – a reaction to the environment indicating the absence of environmental stressors and which is strongly related to health.

5.1. Conceptual framework

From the results of this review, a conceptual framework has been developed, proposing that energy use is a consequence of trying to attain homeostasis (comfort, neutral state, lack of stress).

Consequently, in this framework, the focus lies on the behavioural expressions of comfort (Fig. 2). The link between comfort and energy consumption lies in the active interaction of an occupant with energy consuming products, when trying to achieve this comfort – in particular through the exercise of control and habits. Behaviour is strongly influenced – amongst other factors- by emotions and attitudes, and therefore, these variables have been included in the framework. This is also done since, as presented in this review, habits are highly emotional (emerging from the routine level of emotions) and also counter-attitudinal (due to their unconscious nature).

The feeling of being in control arises by exercising choice, enabled by the presence of environmental choices, while habits are automatic, unconscious, and repetitive behaviours triggered by environmental cues. Such behaviours not only allow the person to cope with stressors and modulate their emotional status towards a more desirable one, but exercising habits and control is also rewarding by itself. "Comfort" as seen from this wider perspective encompasses the subjective feeling of positive emotions and reduction of stress, and as a result it is beneficial to the individual's general wellbeing. However, health is also influenced by several factors in the indoor environment, especially in energy efficient homes.

5.2. Methodological framework

From the conceptual framework, it is proposed to tackle wellbeing (comfort and its links to health) and energy from the perspective of the occupant, and more specifically, their comfort-making behaviours. Because not all occupants have the same needs, values, behaviours, or comfort levels, as a first step, it is proposed to conduct a specialized survey. The purpose of this survey is to find out different occupant profiles, based on their comfort and energy behaviours, and especially the key types of behaviour pinpointed in this review: habits and control.

To achieve so, the survey has to include questions about occupants' emotions (since they guide behaviour), attitudes, and health status. This should be continued by questions about occupants' energy-consuming habits and the strength of such habits. Finally, it has to include the levels of control that occupants need to have over their home environment.

By understanding these five factors (attitudes, emotions, health, control, and habits), which are factors that influence behaviours and that compose important dimensions of 'wellbeing', it should be possible to shed on light on whether there are different types of occupants, and where the differences lie.

The contribution of such an approach is to facilitate the identification of occupant types for the first steps of the engineering process of residential energy consuming technologies (appliances, control systems) but also to contribute to a more comprehensive understanding of comfort for IEQ. The goal of this is to be able provide residential environments – including systems and appliances – that support specific type of users, in terms of their behaviours and needs, so that energy consumption is reduced, while providing 'customized' and optimized wellbeing – comfort and health-.

6. Limitations

The limitations to this review can be categorized as both practical and methodological. The practical limitations lie in the fact that as it is based on the disciplines of the social sciences, namely behavioural psychology, the theories explained are not rigid and definite, but they are based on tendencies. The methodological limitations lie in the fact that there is a lack of research of the topic in the residential context. Theories such as that of the "three-level of emotion" tend to be used solely in the product design context; while

the psychoneuroimmunological approach to wellbeing is as of now non-existent in the home context. Therefore, as social sciences are based on tendencies, changing the 'context' variable might alter the expected and known outcomes of the current tendencies. This is however, the reason why this review was performed, as well as why a new research approach is presented in the form of a methodological framework.

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Appendix A.

Table A1
Scope of comfort by discipline and by human and environmental factors.

		IEQ	Nursing/Healthcare	Ergonomics	Popular	Evolutionary	Domestic	Holistic
Environmental factors	Air quality	+				+ Olfaction/irritation		
	Temperature	+	+			+		
	Visual	+	+			+		
	Acoustical	+	+			+		
	Size/layout						+	
	Interior design (colour, greenery,. . ..)		+ 'Positive stimuli'		+ General environment	+ Environmental stimuli	+	+ General environment
	Other affordances			+		Contextual cues	+	
Human factors	Physiological	+	+		+	+	+	+
	Psychological		+ Psycho-spiritual		+	+	+ Privacy/security	+
	Social		+ Support			+	+ Interaction	
	Physical		+	+		+		+
	Emotional		+		+	+	+ Identification/ Attach-ment/Expression	
	Behavioural	+ Adaptive	+	+		+	+	
	Postural		+	+				

+ Factor is included in that discipline.
Written content: sub-element of the environmental or human factor studied within the discipline.

Table A2
Effects of energy efficient measures on health of occupants.

Reference	Evidence level	Country and date	Variables or indicators		Building type	Population	Effect on health of variables/indicators – Main results
			Indicator	Health			
[89]	1 (systematic review of experimental studies)	Varied, from 1887 to 2007	Warmth measures	Respiratory, general, mental	Varied	Varied	Positive
[91]	1 (systematic review of experimental studies)	Varied, from 1887 to 2012	Housing investments/interventions (warmth measures)	General health (respiratory, absenteeism), illness, wellbeing	All physical house types	All types of participants	Positive
[84]	3 (systematic review of correlational or qualitative studies)	Varied	Light, temperature, air, acoustical	Stress	Laboratory, offices, residences	Varied	Negative
[87]	1 (meta-analysis of experimental studies)	Varied	Insulation, heating, glazing,	General health; respiratory	Varied	36 studies/33000 participants	Positive marginal effects. Improve over time
[99]	1 (review of epidemiologic evidence)	Varied	dampness or mold	multiple allergic and respiratory effects	Varied	Varied	negative
[82]	2 (Community based, cluster, single blinded randomized study)	New Zealand	Insulation (temperature, humidity, energy consumption)	Self-reported, wheezing, days off, GP visits, hospitalization	1350 low income households, uninsulated dwellings.	4407 participants of households with previous respiratory history.	Positive (reduced odds of poor effects)
[85]	6 (narrative synthesis)	England, Wales, Scotland, New Zealand, USA (2000–2009)	Fuel poverty (cold and damp housing)	Mental, physical health	Households	5 studies with more than 2000 households each. Infants and adults	Modest effects in adults, more significant in infants.
[88]	6 (single descriptive qualitative study)	Boston, Chicago, new York city (2009–2012)	insulation, heating equipment, ventilation improvements	self-reported general, respiratory, cardiovascular, and mental health	248 Households	248 adults, 75 children	Positive effect on sinusitis, general health, and asthma medication.
[100]	1 (quantitative meta-analyses	Varied	dampness and mold	respiratory and asthma-related health outcomes	Homes	male adults, female adults, children (Age <18), and infants.	Negative (30%-50% increases in respiratory and asthma related health outcomes)
[96]	4 (case-control study with telephone-administered questionnaire)	New Brunswick and Nova Scotia, Canada (1998)	New homes with heat recovery ventilators	Respiratory symptoms, diagnosed asthma, chronic obstructive lung disease, heart condition, medication use.	53 new homes	149 occupants	Positive effects over 1 year.
[101]	2–3 (Randomized controlled trial, with randomization embedded in study database)	Baltimore, USA	PMs, air nicotine, urine cotinine concentrations	Symptom free days	Johns Hopkins Hospital Children's Center and homes of children	Children with asthma, residing with a smoker, randomly assigned to interventions consisting of air cleaners only (n = 41), air cleaners plus a health coach (n = 41), or delayed air cleaner (control) (n = 44).	Air cleaners reduce PM concentrations and increase symptom-free days. SHS exposure not prevented
[102]	6 (self-administered postal questionnaire)	Sweden	Multiple building characteristics	Asthma, allergy and eczema, hay fever.	472 multifamily buildings	7554 participants	Asthma, allergies or eczema more common with less use of energy for space heating, in larger buildings and in dwellings with redecoration, mold odor, dampness and humid air.
[92]	6 (descriptive-cross-sectional study)	Northeast Texas (2008–2009)	housing characteristics, home interior surface materials, dampness	wheeze, dry cough, rhinitis, eczema	Trailers and apartments.	2819 parents of children	Living in trailers was related to diagnosed asthma and diagnosed hay fever. Central A/C systems associated with an increment of allergic symptoms, especially rhinitis.

Table A2 (*Continued*)

Reference	Evidence level	Country and date	Variables or indicators		Building type	Population	Effect on health of variables/indicators – Main results
			Indicator	Health			
[103]	3 (cross-sectional, correlational)	Sweden	Water leakage, visible dampness, floor moisture, window condensation	Wheeze, cough, eczema, rhinitis, asthma	8918 homes.	10,851 children (1–6 years)	Dampness indices were associated to higher prevalence of symptoms
[81]	2 (randomized to waiting list)	Devon UK	Upgrading houses (including central heating, ventilation, rewiring, insulation, and re-roofing)	General health Respiratory health. Musculoskeletal health. Health service contacts. Hospital admissions.	119 council owned houses	480 residents of these houses.	lessening of asthma symptoms in adults and appears to protect against non-asthma respiratory conditions in adults and children
[94]	6 (Postal questionnaire)	United Kingdom	household energy efficiency	Asthma outcomes	3867 social housing properties	944 participants	Increased energy efficiency may increase risk of current asthma. Moldy/musty odor associated with risk of asthma
[95]	1 (systematic review)	varied	particle filtration	Self-reported health and measured allergy, asthma, inflammation, respiratory system performance, lung function, blood pressure, heart rate.	Non-industrial buildings (homes, schools, and offices)	Varied	Particle filtration modest effect in reduction allergy and asthma outcomes. Not very effective in reducing acute health symptoms in non-allergics/asthmatics. Morbidity and mortality associated with particle exposure is reduced.
[104]	2 (double-blind, randomized trial)	area surrounding Cincinnati, USA	Air nicotine levels, tobacco smoke exposure, indoor airborne particle levels, and exhaled nitric-oxide levels	unscheduled asthma visits and symptoms	Homes of participants.	225 children (6–12 y.o.) with asthma, exposed to SHS	HEPA air cleaners may reduce asthma morbidity
[80]	1 (Systematic review of experimental and non-experimental)	Varied	interventions to improve housing (rehousing, refurbishment, and energy efficiency measures)	health effects	Varied	Varied	Most studies found some health gains, but inconclusive evidence due to small samples.
[90]	1 (systematic review of intervention studies)	Varied	energy efficiency interventions (warmth, affordability of fuel, psycho-social factors, indoor air quality)	Physiological, social, psychological health.	Residences	Varied	EEI improved winter warmth and lowered relative humidity with benefits for cardiovascular and respiratory health.
[105]	6 (narrative synthesis)	UK	energy-efficient measures	General health	UK homes	Varied	Poor ventilation, overheating, poor IAQ may affect health.
[106]	1 (systematic review)	USA and UK	thermal exposures	obesity prevalence	domestic setting	Adults	Plausible causal link between increased time spent in thermal comfort and increased adiposity in the population
[107]	3 (systematic review of correlational; qualitative studies, RCT or quasi-experimental studies)	Varied	Climate change; indoor exposures; changes in the building.	General health	Varied	Varied	Health effects of climate change will result from indoor exposures. Climate-related health effects can be reduced by changes to buildings. Changes to buildings will improve health irrespective of climate change. Changes to buildings will save energy and reduce CO2 emissions.
[108]	3 (descriptive correlational study)	England (2001–2003)	Warm front energy efficient measures (insulation and insulation)	Temperatures in household.	Dwellings with Warm Front measures	Varied	Temperatures influenced by property characteristics (age, thermal efficiency, number of people, age of the head of household). Warm front measures improve living- and bedroom temperatures

Table A2 (*Continued*)

Reference	Evidence level	Country and date	Variables or indicators		Building type	Population	Effect on health of variables/indicators – Main results
			Indicator	Health			
[86]	3 (systematic review of correlational; qualitative studies, RCT or quasi-experimental studies)	Varied	Indoor environmental factors	Health outcomes (communicable respiratory illnesses; allergy and asthma symptoms; sick building syndrome symptoms)	Varied	Varied	Characteristics of buildings and indoor environments influence SBS, respiratory, and allergy and asthma symptoms. Marginally adequate indoor environment provision can be replaced by health promoting IE
[109]	3 (Descriptive correlational study)	Nine European countries	building energy performance; building characteristics and IE	Feeling and perception of IE; SBS	Apartment and office buildings	Dwellers and office workers	Low Energy buildings with good IE exist.
[110]	3 (Descriptive correlational study)	Nine European countries	building energy performance; building characteristics and IE	Feeling and perception of IE; SBS	Apartment and office buildings	Dwellers and office workers	Low Energy buildings with good IE exist.
[111]	3 (Descriptive correlational study)	European countries	perceived indoor air quality.; pollution sources; ventilation rates and performance; energy consumption	symptoms/complaints	office buildings	Office workers	Occupants acceptability and BRS shows no correlation with perceived IAQ
[112]	3 (Descriptive correlational study)	Netherlands	Cold acclimatization	BAT production, NST thermogenesis.	Laboratory	17 healthy men and women	Repeated intermittent cold exposures recruited brown adipose tissue; accompanied by an increase in non-shivering thermogenesis
[113]	3 (Descriptive correlational study)	Netherlands	Thermoneutral conditions (22C) and mild cold exposure (16C)	Body composition and energy expenditure; Brown-adipose-tissue activity	Laboratory	24 healthy men (10 normal weight- 14 overweight or obese)	BAT activity is reduced yet present in most overweight or obese men, thus may be a target for the treatment of obesity
[83]	6 (longitudinal questionnaire – single descriptive qualitative study)	Japan	–	Chronic back pain; Satisfaction with living environment; Stress and fatigue	–	Japanese women 3054	Causal effect: “stress and fatigue” –>“chronic back pain”. Second causal effect: “satisfaction of living environment” –>“stress and fatigue.” Thus, suggestion that “satisfaction of living environment” influences “stress and fatigue” which is manifested as “chronic low back pain”.
[114]	5 (systematic reviews of descriptive and qualitative studies.)	Varied	indoor air pollution; energy-efficient homes	General health	Varied	Varied	Evidence of effects of indoor air pollution and health links is strong and partly quantified. Effects of energy-efficient homes on health, evidence is meagre.
[115]	(5 (systematic reviews of descriptive and qualitative studies.)	Varied	housing quality, housing characteristics	asthma expression; psychological stress	Varied	Children	Increasing evidence has linked psychological stress and negative affective states to asthma expression

+ Factor is included in that discipline.
Written content: sub-element of the environmental or human factor studied within the discipline.
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