Building and Environment 179 (2020) 106928

Contents lists available at ScienceDirect

Building and Environment

journal homepage: http://www.elsevier.com/locate/buildenv

What drives our behaviors in buildings? A review on occupant interactions with building systems from the lens of behavioral theories

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ARTICLE INFO

Keywords:
Behavioral theories
Occupant behavior
Building systems
Energy efficiency

ABSTRACT

Occupant behavior has a significant impact on building systems' operations and efficiency. As a result, several innovative approaches have been introduced to quantify the dynamics of occupants within indoor environments, such as interactions with different building systems and the impact of various feedback and interventions to reduce the building energy consumption. To achieve this, researchers have highlighted the importance of reducing energy consumption without impacting occupant comfort. As a result, there is an increasing body of research evaluating how different theories of behavior across a variety of disciplines can explain occupant interactions with building systems. Future progress in this area calls for an in-depth understanding of behavioral theories in explaining occupant interactions with different building systems. In this paper, we have used a structured literature review approach to investigate how different psychological, sociological, and economic theories have been applied to explain occupant interactions with heating and cooling (HVAC systems), opening windows and ventilation, lighting and shading, electronic appliances, domestic hot water, as well as energy conservation behaviors. Throughout the paper, we identify the most common theories and methodologies applied within the existing research, general findings related to how occupants interact with different building systems, as well as a number of identified gaps within the literature. Finally, we provide a discussion on directions for future research studies in this area under each building system.

1. Introduction

Buildings and their energy management systems account for a considerable portion of energy consumption worldwide [1]. To reduce the total energy consumption in buildings, a large stream of research has focused on improving the technology, design, and operation of building systems. These improvements, including the research on the interaction between occupants and building systems, have shown great potential to reduce building energy consumption [2,3]. Therefore, Human-in-the-loop (HITL) building-system operations have received considerable attention in recent years due to the advances in technologies for sensing/actuation and their prevalence as consumer products [4]. Studies have focused on understanding and facilitating human-building interaction (HBI) modalities and how they could be leveraged for energy efficiency mainly in the form of optimization-based control techniques. An overview of the academic research and product development efforts show that interactional behaviors that received considerable attention in recent years can be categorized as: (1) spatiotemporal patterns of occupancy, (2) occupant perceptions and preferences for the indoor ambient conditions (e.g., thermal, visual, and

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https://doi.org/10.1016/j.buildenv.2020.106928
Received 30 November 2019; Received in revised form 10 April 2020; Accepted 13 April 2020
Available online 13 May 2020

acoustic comfort), (3) occupant awareness of the energy and environmental implications of operations (i.e., studies on eco-feedback in indoor environments), (4) occupant interaction with appliances and control interfaces, and (5) occupant activity level [4]. Although these modalities could be correlated in nature (as one modality could impact the others), the research synthesis studies have commonly referred to these broad categories for characterizing their contributions.

The majority of these studies have focused on innovative means and methods for quantifying the occupants' behavioral patterns and preferences in indoor environments and optimizing the operation of building systems accordingly [4,5]. Occupancy (e.g. Refs. [6,7]), comfort including thermal, visual, and acoustic, etc. ([8–10]), and interactions with different control interfaces (both mechanical and digital) such as lighting control, windows/doors opening and closing, thermostats, and appliances (e.g., Refs. [11–13]) are among the main modalities. Another set of studies focuses on energy feedback systems for behavioral interventions toward energy efficiency in buildings (e.g., Ref. [14–16]). Highlighting the important role of occupant behavior on building energy consumption, researchers have emphasized that interventions and energy reduction strategies should focus on resource efficiency without impacting occupant comfort [17]. In other words, such strategies should be occupant-centric by considering factors such as personal preferences and expectations, personal (moral) and social norms, economic motivations, and cultural norms.

As energy efficiency studies have become more occupant-centric, a growing number of researchers have pointed to the importance of understanding the underlying drivers of occupant behaviors from the lens of behavioral sciences and have suggested their integration with engineering dimensions [18–24]. As a result, there is an increasing body of research that investigates how different behavioral (ex. psychological, sociological, and economic) theories can explain occupant behaviors and interactions with different building systems [25]. At the same time, previous reviews concluded that overall very few articles in the field mention theories related to their study design or when discussing their results [26]. Seeking to understand the state of the art in the field, this research thus sought to conduct a comprehensive review of these studies, assessing the extent to which behavioral theories have been applied to understand the relationships between users, building systems, and energy consumption. To our knowledge, this is the first paper to explicitly analyze the ways in which behavioral science has been used to understand different building systems and thus believe this review provides an important contribution to the field.

1.1. Objectives and structure

Pursuing the drivers of observed behaviors in the context of building systems, our objectives in this review include:

1. Identifying the psychological, sociological, economic theories and their associated elements (constructs) that have been applied to understand interactions of occupants with one or multiple building energy systems
2. Understanding to what extent these theories have been leveraged in the literature to characterize occupants' interactions with building systems
3. Providing a review of research methods that have been applied to conduct such studies
4. Identifying the characteristics of such studies including the geographical locations, types of buildings, number of participants, and their findings
5. Discussing the existing research gaps and roadmap for future research in this area

This literature review is organized according to building system types (HVAC, window opening and ventilation, lighting and shading, electronics devices and appliances, domestic hot water) following the breakdown suggested by Ref. [27]. We use the term *mixed systems*, if a given study collectively accounts for or examines current and intended use of more than one individual building system. For example, a study that assessed energy savings associated with HVAC, ventilation, and domestic hot water according to a psychological theory but only reported metrics according to aggregate energy savings would be considered mixed systems. If the same study reported metrics specific to each building system, it would also have been included in this review but analyzed according to each individual system. Alternatively, studies that reviewed building systems identified in Ref. [27] but did not warrant their own category, such as individual adjustments, or explored occupant behavior in buildings without explicitly discussing systems (ex. from an energy or water conservation perspective), we also coded as mixed systems. Throughout the paper, for each type of building system, we (i) discuss the methodologies used across studies, (ii) reflect on the applied behavioral theories, (iii) describe the general findings, and (iv) present the research gaps.

The rest of this paper has been structured as follows:

- Section 2 provides an overview of the systematic literature review methodology and selection criteria of the related literature.
- Section 3 identifies the studied theories and their associated constructs along with example applications.
- Section 4 provides a comprehensive overview of the theories applied in identifying occupant interactions with specific building systems:
  - HVAC Systems
  - Windows Opening and Ventilation
  - Lighting and Shading
  - Electronic Devices and Appliances
  - Domestic Hot Water
  - Mixed Systems
- Section 5 discusses the current shortcomings of existing research and provides suggestions for future research studies in this area.
- Section 6 presents a conclusion.

2. Methodology and selection criteria

To compile the literature review in this paper, we first conducted a search for relevant studies, published within the previous 20 years. The last two decades were selected as there have been significant technological developments and improvements in the HBI domain within this timeframe. The goal was to identify studies that had been guided by a behavioral theory, specifically applying one or more such theories to the understanding or predicting interaction with at least one building system. The literature search was conducted using the following databases: Academic Search Complete, PsycInfo, Scopus, Web of Science, and Google Scholar. Search strings included multiple combinations of the following keywords (* represents multi-character truncated search terms - i.e., wildcard):

- Building system-related keywords (building system, HVAC, cooling, heating, light*, shade*, blind*, adjustment*, adaptation, hot water, water heat, electron*, appliance*, device*, window*, ventil*, action, clothing, body, posture, activity level, drink, eat, shower, hand);
- Occupant-related keywords (resident*, occupant*, employee*, individual, personal);
- Theory-related keywords (theory, psyc*, socio*, econom*);
- Building-related keywords (building*, work, home, built environment);
- and general, topic-related keywords (energy, consum*, behavior)

\The search resulted in approximately 265 articles that went through an inclusion/exclusion process (135 included/130 discarded). Because a minority of the studies explicitly applied or tested a behavioral theory, any study that used at least one psychological, sociological, or economic factor was included in this review in order to predict or explain occupant interactions with building systems. Studies that did not explicitly examine and provide data regarding the influence of at least one factor on occupant interaction with at least one energy-related building system were excluded. Types of studies that were most often rejected included those that were reviews of the literature or systematic reviews; those that might have used a term of interest (e.g., psychological) in the literature review, but did not ultimately examine or report the influence of a behavioral theory/factor on interactions; studies that examined the purchase of energy-efficient appliances or systems; or those that focused on different feedback mechanisms without providing insights on behavioral theories/factors that may motivate occupants in reducing energy consumption. In order for a study to be rejected, at least two authors had to agree that it was not appropriate and should be rejected.

We further note that, in this review, the scope is limited to the intentions and immediate actions of occupants that can be explained by behavioral theories. Specifically, physiological factors or feedback and intervention strategies that can motivate occupants to reduce their energy consumption behaviors are not within the scope of this work.

3. Overview of the identified behavioral theories

In this section, we provide an overview of the behavioral theories identified during our review, with the goal of providing the reader with a high-level perspective on these behavioral theories and examples of their applications in describing occupant interaction within building systems (Table 1). While a multitude of theories exist across different disciplines, this review includes references to 27 specific theories that emerged in the studies we identified.

Throughout this paper, we present studies that used theories and/or their constructs to predict or explain interactions with building systems. *Theories* formalize behavioral manifestation and the *constructs* within the theory describe latent variables that drive those manifestations. For example, the Value, Belief, Norms Theory (VBNT) proposes that one's behavior (e.g., energy saving behavior) is driven by personal values and norms, both of which are constructs within that theory (Fig. 1). It is important to note, some of the reviewed papers have referenced or employed both theories and the associated constructs in describing system interactions. However, some other papers only referenced the constructs without explicit description of the theories. These studies are further discussed within Section 4.

As shown in Table 1, the identified studies applied psychological theories significantly more often than sociological or economic theories. Within psychological theories, the Theory of Reasoned Behavior/Theory of Planned Behavior, Norm Activation Model, Value Belief Norm, and Theory of Interpersonal Behavior received the most attention. Fig. 1 provides an overview of the top five most commonly applied psychological theories along with their specific constructs, and their relationships. In sections 3.1 and 3.2, we provide examples of more commonly studied psychological and sociological theories, along with their constructs and applications in explaining occupant interactions with buildings systems. For more detailed summary of the theories identified in Table 1, please refer to supplementary documents as well as the references provided on the left column of Table 1.

3.1. Example 1: Theory of Reasoned Action/Theory of Planned Behavior (psychological)

These theories seek to predict human behaviors and make the assumption that the best predictor of a given behavior is one's intention to perform it within a given time frame and context [28]. These intentions are formed by one's consideration of accumulated beliefs about the consequences of performing the behavior. The Theory of Planned Behavior (TPB) is an extension of the Theory of Reasoned Action (TRA). Fig. 1 provides an overview of the constructs within TRA/TPB.

Table 1
Identified theories and the corresponding reviewed studies. On the left column, the theories are their references are presented. On the right column, the reviewed studies that leverage these theories are presented and categorized based on different building systems.

Theory	Identified studies
Psychological Theories	
Theory of Reasoned Action (TRA) and Theory of Planned Behavior (TPB) [28–30]	• HVAC: [31] • Lighting and shading: [32,33] • Appliance and electronic devices: [32,34,35] • Domestic hot water: [36] • Mixed systems: [37–51]
Theory of Interpersonal Behavior (TIB) [18,52,53]	• Appliance and electronic devices: [54] • Mixed systems: [45]
Norm Activation Model (NAM) [55,56]	• HVAC, window opening and ventilation, lighting and shading, and appliance and electronic devices: [57] • Mixed systems: [37,40,43,57,58]
Value Belief Norm Theory (VBN) [59]	• Mixed systems: [42,60–63]
Perceptual Control Theory (PCT) [64–66]	• Mixed systems: [66]
Social Cognitive Theory (SCgT) [67]	• Appliance and electronic devices: [68] • Mixed systems: [68]
Social Comparison Theory (SCmT) [69,70]	• Appliance and electronic devices: [71]
Construal Level Theory (CLT) [72,73]	• Domestic hot water: [74]
Self-Regulated Behavior Change [75]	• Mixed systems: [76,77]
Self-Determination Theory (SDT) [78]	• Window opening, lighting and shading systems: [79] • Mixed systems: [80]
Goal Framing Theory [81–83]	• Lighting and shading: [84] • Appliance and electronic devices: [71]
Functional Attitude Theory (FAT) [85]	• Mixed systems: [86]
Technology Acceptance Model (TAM) [87–90]	• Mixed systems: [50]
Protection Motivation Theory (PMT) [91–93]	• Mixed systems: [94]
Motivation Opportunity Ability (MOA) [95]	• Lighting and shading: [96] • Mixed systems: [37,96]
Hierarchical Theory of Needs (Maslow's) [97]	• Window opening, lighting and shading systems: [79]
Drivers Needs Actions Systems Framework (DNAS) [98,99]	• Domestic hot water: [100]
Observe Orient Decide Act (OODA loop) [101]	• Lighting and shading: [33]
Sociological Theories	
Social Practice Theory (SPT) [102–105]	• Appliance and electronic devices: [106,107] • Mixed systems: [105,107–110]
Energy Cultures Framework [111–113]	• Mixed systems: [111,114,115]
Socio-Technical Systems (STS) [116]	• Mixed systems: [117]
Social Network Theory (SNT) [118–120]	• Mixed systems: [110,121]
Actor-Network Theory (ANT) [121,122]	• Mixed systems: [119,123]
Economic Theories	
Game Theory [124,125]	• HVAC, lighting and shading systems: [126]
Discrete Choice Theory [127,128]	• HVAC, lighting and shading systems: [126]
Framing Theory [129]	• Mixed systems: [130]
Theory of Self Control [131]	• Mixed systems: [132]

3.1.1. Core constructs

Behavior represents whether or the extent to which one typically practices a given behavior. ***Behavioral intention*** represents the extent to which an individual intends or plans to practice a given behavior within a given time frame and context. ***Attitudes*** reflect an individual's beliefs about likely positive and negative consequences of performing a particular behavior. ***Subjective norms*** (also called social norms) are individuals' beliefs about the extent to which important others expect them to engage in the behavior. ***Perceived behavioral control*** (not included in the Theory of Reasoned Action, but added with the Theory of Planned Behavior [29]) represents individuals' beliefs about their ability to enact the behavior (capacity) and whether or not their actions are completely under their control (autonomy).

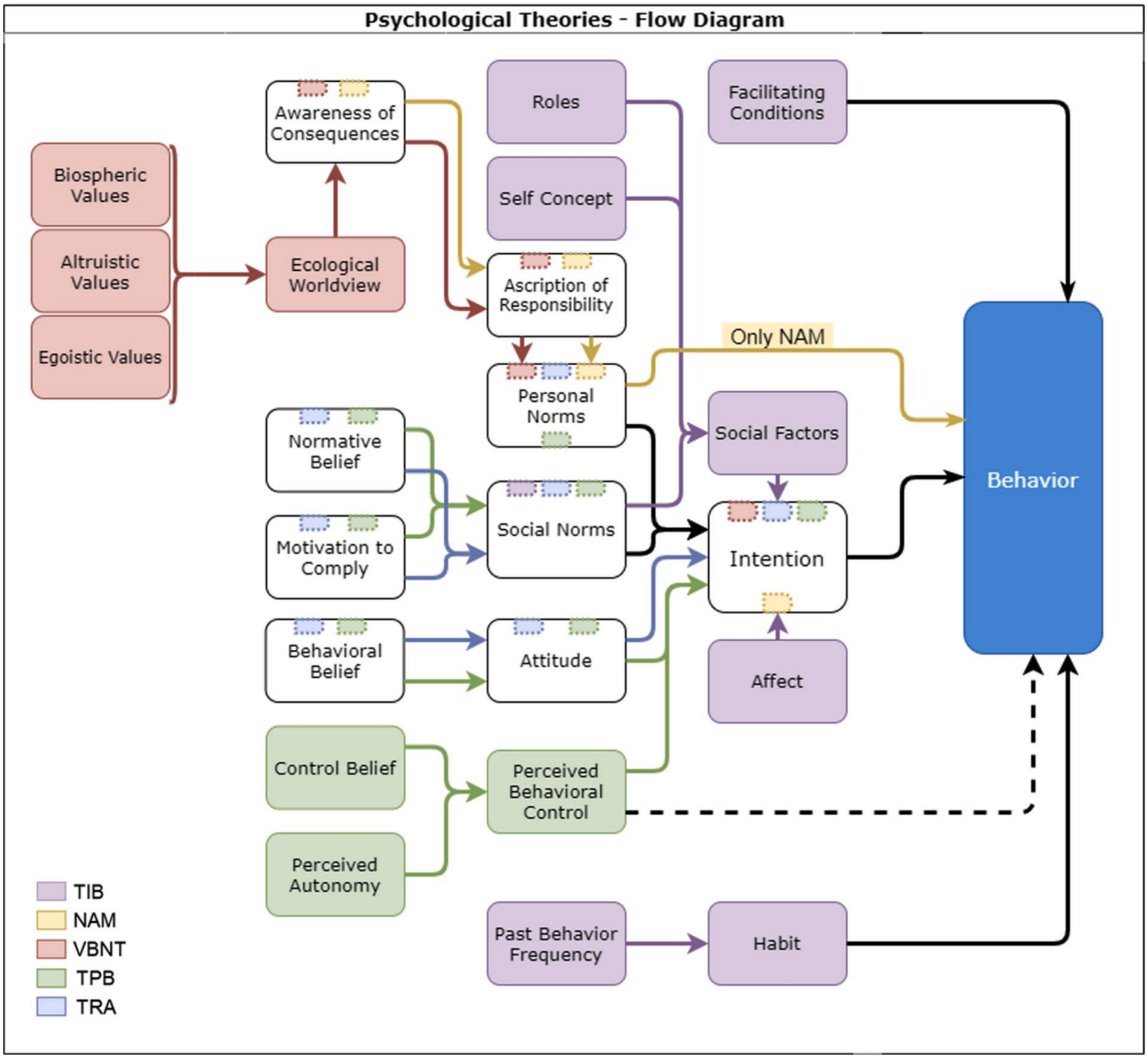

Fig. 1. Overview of the five most commonly applied psychological theories within the identified manuscripts along with their constructs (TRA – Theory of Reasoned Action, TPB – Theory of Planned Behavior, NAM – Norm Activation Model, VBNT – Value, Belief, Norm Theory, and TIB – Theory of Interpersonal Behavior). The constructs associated to each theory are shown as a box, with a specific color associated to a specific theory – see legend. Note some constructs are commonly used among different theories; those have multiple color boxes associated to them. Please note in TPB, the dotted line indicates that perceived behavioral control directly and indirectly (through intentions) has an effect on behaviors. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Behavior is predicted directly by behavioral intention. Behavioral intention is predicted by attitudes, beliefs about subjective norms, and perceived behavioral control. Of note, the influence of these three variables/constructs on behavioral intentions will vary in strength, depending on the given behavior. For example, for very easy behaviors, attitudes should be more influential than perceived behavioral control.

3.1.2. *Example application*

Ding et al. [31] found that residents' positive attitudes toward saving energy and their beliefs that others expected them to save energy (subjective norms belief) predicted their intentions to save energy related to home heating; greater intentions to save energy, in turn, had a positive influence on residents' heat-use habits and the purchase of energy-saving products for home heating. However, neither perceived behavioral control nor descriptive norms beliefs predicted intentions or behaviors related to saving energy for heating.

3.2. *Example 2: Energy Cultures Framework (sociological theory)*

The Energy Cultures Framework was initially developed as a way to support interdisciplinary research on energy behaviors, serving as a communication tool to bridge disciplinary differences in language. Energy cultures exist at a multitude of scales, including the individual, household, and business. The framework seeks to describe how behavior or practices are embedded within both the physical and social contexts of life, focusing on "energy cultures," or the interrelationships between norms, practices, material cultures and external factors, as the unit of analysis [111,112].

3.2.1. *Core constructs*

Norms represent shared beliefs on how individuals should behave in a given context, expectations and/or aspirations about what we do and what we have. ***Material culture*** represents the technologies and infrastructures that influence the use of energy, both functional and symbolic. ***Practices*** represent "usual or customary actions." They acknowledge most actions that impact energy consumption are not targeted at energy use itself but the services it provides. They include both routine behaviors and infrequent actions that are common among a social group. ***External influences*** include transactional and contextual environments. Agents interact and influence transactional environments while they respond and adapt to contextual ones. These external influences are typically beyond the control of the subject.

3.2.2. Example application

Lazowski et al. [115] assessed the impacts of a smart home user interaction interface for a smart grid pilot project through the lens of the Energy Cultures Framework. Through analyzing data collected with surveys and interviews it was investigated how the study (1) affected occupants' attitude and awareness towards energy management (***norms***), (2) influence behaviors regarding use of appliances and/or thermostats for energy conservation or peak shaving (***practices***), and (3) encourage equipment upgrades such as more efficient appliances (***material infrastructure***). Through these analyses, the authors concluded that in addition to ***external influences*** such as pricing structures, existing lifestyle expectations surrounding comfort (***norms)*** and low prices (***external influences***) ultimately limited adoption of more sustainable energy cultures.

4. Synthesis of the application of behavioral theories in building systems

In this section, we provide a synthesis review on how different behavioral (psychological, sociological, and/or economic) theories (or elements/factors within these theories) mentioned in the previous section have been applied to understand and predict occupant interactions with different building-systems. To clearly identify how these theories have been applied, we have broken down the identified research studies based on occupant interaction with specific building-systems. As a result, in the following subsections we provide an overview of the applied behavioral theories explaining occupant interactions with HVAC system (section 4.1), window opening and ventilation (section 4.2), lighting and shading (section 4.3), electronic devices and appliances (section 4.4), domestic hot water (section 4.5), and energy conservation behaviors and mixed building systems (section 4.6). Due to the significant number of papers applying different behavioral theories to explain energy conservation behaviors and mixed building systems, we have divided Section 4.6 into four subsections. In section 4.6.1, 4.6.2, and 4.6.3 we focus on the applied psychological, sociological, and economic theories, respectively; in section 4.6.4, we provide a holistic discussion across all three theoretical backgrounds applied to energy conservation and mixed systems. Within each subsection, we provide an overview of the applied theories and methodologies, data collection techniques, general findings, and the geographical locations where these studies were conducted.

4.1. Occupant interactions with HVAC systems

In the context of heating and cooling studies, human behavior has been characterized in terms of preferences and interactions with heating/cooling interfaces (e.g., thermostats and mobile devices) as well as adaptive behavior (e.g., adjustments of the clothing level) [133]. Besides studies on predicting and quantifying occupancy patterns for cooling/heating load management, in recent years, several studies have focused on evaluating and quantifying thermal comfort perception and preferences [10,134]. The objectives, in these studies, have centered around developing models that predict the perception or preference of occupants according to the ambient indoor conditions to be used primarily for context-aware and intelligent control [4]. In doing so, thermophysiological features have received increasing attention in recent years as they have shown to be effective in improving machine intelligence for modeling purposes [4,10,134–137]. However, other factors, including social, psychological, and economic drivers could result in significant implications (besides the need for thermal comfort) for occupant behavior and be associated with their use and control of heating/cooling systems [138,139].

Among the studies identified for this review, a limited number of studies (n = 10) have explicitly pointed to concepts from behavioral theories in investigating occupant interactions with HVAC systems [31,57,126,140–146]. Human interactional and adaptive behaviors have been primarily investigated in a larger scope and across multiple building systems - i.e., mixed systems and energy conservations which are discussed in Section 4.6. Table 2 provides an overview of the studies focusing on the applied behavioral theories to identify occupant interactions with the HVAC system.

4.1.1. Theoretical approaches and general findings

Of the 10 studies reporting occupant interactions with HVAC systems, only three were explicitly guided by a behavioral theory. These studies are described in detail below; the other seven studies that were not explicitly guided by a behavioral theory will be summarized.

Within the studies explicitly guided by a behavioral theory, Ding et al. [31] surveyed residents of Shanghai, China, about their heat-saving behaviors, using the Theory of Planned Behavior as a framework. The study found that energy-saving attitudes and subjective norm beliefs were significant predictors of intentions to save energy related to home heating; in turn, those intentions had a positive influence on heat-use habits and the purchase of energy-saving products for home heating. The authors also concluded perceived behavioral control and descriptive norms beliefs did not predict intentions or behaviors. Konstantakopoulos et al. [126], used game theory and discrete choice models to design and test the effects of playing a non-cooperative social game on energy use. The authors concluded playing the game to earn points and rewards lead to reduced use of air-conditioning in student dormitory rooms in Singapore. Matthies et al. [57] used a modified version of the Norm Activation Model (NAM) to guide the design of a communication intervention for non-residential buildings in northern Germany. The intervention strategy was based on survey data on existing energy-saving behaviors of employees along with their stated motives for saving energy at work and awareness of consequences. The intervention included messages informing occupants that the energy-saving program was good for the environment and would save the organization money (i.e., the messages emphasized beliefs about consequences occupants already possessed), a "stabilization of personal norms" (employees were asked to send in a private “energy saving” commitment form), and coupons for power strips in order to lower cost/barriers to energy-saving behavior (this was an attempt to enhance occupants' perceived behavioral control to use less energy in the workplace). Over time, the treatment/intervention group reduced heating more than the control group; however, the sample size was too small to test for significant differences. Additionally, compared to occupants in the control group, those in the treatment/intervention group reported a marginally significant increase in the behavior of turning-off heating during manual ventilation.

The other seven studies identified for this review (that were not explicitly guided by a behavioral theory) examined how interactions with HVAC systems were associated with or influenced by variables such as attitudes [140,141,146], values [142], beliefs [141,145,146], prior behaviors [141,144], cultural background [144], receiving feedback on energy use [140,143], or making public commitments to a behavior [143]. Two studies examined the role of attitudes in predicting the use of HVAC systems [140,146]. These studies found that attitudes toward saving energy in order to save money [140,146], attitudes related to thermal comfort [146], attitudes toward saving energy to protect the environment [140], and attitudes toward saving energy for social motivations [140] predicted system interactions. In another study the role of residents' personal values in room temperature settings at night was examined [142]. In this study, stronger biospheric values were found to

Table 2
Overview of studies applying different behavioral theories to explain occupant interactions with HVAC systems (abbreviation definitions of theories are listed below the table). Some of the identified studies only investigated specific constructs without specifying a theory (identified by '-' under the Theory column).

Manuscript	Theory	Constructs	Method	Analysis	Sample size	Building type	Country
Schweiker and Shukuya, [144]	-	Prior behavior, cultural background	Survey, monitoring AC state	Logistic Regression	32 single-occupant rooms	Residential	Tokyo, Japan
Matthies et al. [57]	NAM (modified)	Awareness of consequences, personal norms, and lower cost of behavior	Experimental design	ANOVA	15 buildings/ 2041 participants (university staff)	University buildings	North Rhine-Westphalia, Germany
Lange et al. [141]	-	Attitude, beliefs, prior behavior	Survey	Multiple Regression	8144 households	Residential	United Kingdom
Yang et al. [146]	-	Attitude, beliefs	Survey	Hierarchical Regression	427 households	Residential	England
Wolff et al. [145]	-	Beliefs	Mixed method: Interviews, electricity bill	Qualitative Data and Descriptive Statistics	80 households	Residential	Ulm and Munich, Germany
Outcault et al. [143]	-	Feedback, making public commitment	Experimental design	Descriptive Statistics	18 participants	Residential	E-Sogo in Japan and West Village in California, United States.
Erell et al. [140]	-	Environmental awareness, attitude to environmental issues	Experimental design	Multiple Regression	114 households	Residential	Jerusalem and Nesher, Israel
Ding et al. [31]	TPB	Energy-saving attitudes; subjective norms; beliefs; perceived behavioral control; and descriptive norms	Survey	Multiple Regression	215	Residential	Shanghai, China
Konstantakopoulos et al. [126]	Game theory; Discrete choice theory	Gamification, feedback, competition	Experimental design	t-tests	72 rooms	Residential (dormitory)	Nanyang, Singapore
Namazkhan et al. [142]	-	Values	Survey	Proportional Odds Logistic Regression Model	1461 households	Residential	Netherlands

NAM – Norm Activation Model; **TPB** – Theory of Planned Behavior.

reduce the use of heating; while stronger egoistic values were found to increase heating use. Altruistic and hedonic values had mixed effects on heating use. Additionally, two studies examined the role of feedback on the use of heating and/or cooling systems [140,143]. In both studies, providing users with feedback on energy use related to heating or cooling did not influence subsequent use. Finally, Wolff et al. [145]'s qualitative study in Germany found that residents attributed "energy literacy" (knowledge of heating system functionality), the difficulty of regulating their systems, and their perceptions of comfortable temperatures to their own regulation of thermostats and room temperatures. Of note, some factors across these seven studies were found not to have an influence on interaction with HVAC-related systems in residential settings; these included moral norms (measured as the belief that one had a "personal responsibility to save energy") [146] and feedback [140,143].

Only one of the 10 HVAC-related studies identified for this review was conducted within a non-residential setting: Matthies et al.'s [57] examination of the effects of a communication intervention (intervention vs. control group) among 15 university buildings in Germany. As discussed above, only a marginally significant effect of the intervention was found for self-reported heat regulation related to window tilting.

In summary, across these studies, interactions with HVAC systems in residential settings were typically associated with attitudes related to thermal comfort; financial, environmental, and social motivations to reduce energy consumption; biospheric and egoistic values; subjective norms beliefs; prior behavior or habits related to saving energy (i.e., adjusting clothing); cultural background; and system-related knowledge. Of note, one study on residential heating expenditures found no significant influence of climate-change risk beliefs or pro-environmental attitudes on heating energy use [141]. Mixed evidence was found for the influence of descriptive norms beliefs and altruistic and hedonic values. No significant effects of feedback on energy use were identified. For non-residential settings, the results of one study indicated that interventions addressing occupants' motivations, moral norms, and perceived behavioral control (or self-efficacy) to save energy can somewhat reduce heat energy use [57].

4.1.2. Methodological approaches

Of the studies examining interactions with HVAC systems, four employed quantitative surveys [31,141,142,146]; four used an experimental design [57,126,140,143], and one used a mixed-method including in-depth interviews and data from participants' electricity bills [145]. Another study included monitoring of air conditioning state along with a quantitative survey [144]. Nine of the 10 studies were conducted in residential settings [31,126,140–146]. This pattern could be associated with the fact that users have more autonomy and responsibility in residential settings, compared to non-residential environments, in which facility managers are primarily in charge of adjusting the control settings. The autonomy available to occupants in residential settings could better reveal the range of user behaviors.

4.1.3. Discussion and identified gaps

Overall, a limited number of studies have examined different behavioral theories and predictors. In recent years, there has been an increase in the number of studies evaluating thermophysiological drivers. One reason for this increase could be due to improved and cost-efficient sensors and computational capabilities. However, there is a need for a greater understanding of how socio-psychological-economic factors influence behaviors in isolation and in combination with thermophysiological drivers. In other words, by understanding the role of such factors, intelligent and adaptive operations of building systems could benefit from an additional dimension for more effective context-aware operations rather than just focusing on ambient and thermophysiological conditions. Additionally, the majority of identified studies are purely self-reported, and there is a lack of experimental and naturalistic studies in real-world environments. Through conducting naturalistic studies, specific interactional and adaptive behavior modalities including adjustment of clothing, interacting with thermostats, and feedback through different mediums (e.g., web-interface and mobile platforms) can be better studied. Other factors such as cultural differences were identified to impact occupant behaviors. Among the studies identified for this review (as shown in Table 2), there are only a few countries and geographical locations in which the impact of behavioral factors on occupant HVAC-system interactions were studied. Therefore, more studies should be conducted in different geographical locations to better capture the behavioral differences in occupant interactions with the HVAC systems.

4.2. Occupant interaction with windows and ventilation systems

Similar to the previous section, there are a limited number of studies that explicitly focused on concepts from behavioral theories in investigating occupant window openings and ventilation behavior. Specifically, we identified nine papers that investigated these interactions using different behavioral theories [57,79,145,147–152]. Their objectives can be divided into three categories: (1) an increased understanding of the effect of interventions [57,147,151]; (2) interactions between building design and behavior [145,149,150]; or (3) the behavior itself [79,148,152]. Table 3 provides an overview of these studies.

4.2.1. Theoretical approaches and general findings

Studies looking at the effect of interventions on window opening and ventilation behavior confirm the importance of psychological, social, and/or economic considerations when designing an intervention measure. Ornaghi et al. [147] showed that feedback about relative performance leading to the feeling of competition, social comparison, or social pressure is effective in promoting pro-environmental behavior. Furthermore, the authors concluded that even short treatments have a lasting effect of several weeks on occupant behavior. DellaValle et al. [151] concluded that ventilation behaviors are part of "culturally recognized social practices" (p. 521) – individual preferences play a minor role. Ventilation behavior in summer and winter can be explained by factors such as knowledge, perceptions, and satisfaction. Furthermore, the authors highlighted that strategies for changing a behavior need to be adjusted based on whether the behavior is considered a part of a wider social practice or dependent on individual preferences. Matthies et al. [57] revealed that a significant increase in observed and self-reported closed windows in winter can be achieved by interventions based on their modified Norm Activation Model.

The three studies with the objective to identify potential interactions between building design and window opening and ventilation behaviors applied Social Practice Theory. Galvin [150] explains the largely applied behavior of trickle ventilation, which has a large impact on heating energy use, with objectively observable aspects, such as pot plants preventing the full opening of windows together with subjective aspects. The latter are the perceived efficiency, effectiveness, and economic efficiency of trickle ventilation in combination with the participants' strong affinity (attitudes) for pot plants. The author discusses the results related to pot plants in light of classical Social Practice Theory, which includes "skills, knowledge [.], routinized bodily actions [.], material objects [.], emotional attachments and shared meanings" (p. 37) [150]. Wolff et al. [145] also mention a mismatch between materiality (newly refurbished apartments) and practice (former heating and ventilation behavior) in combination with meanings (the need for fresh air), competences (different levels of knowledge regarding ventilation strategies). Hansen et al. [149] conclude that building-related influences such as the existence of mechanical ventilation with heat recovery and demographics have an influence on the frequency of opening windows, while the energy efficiency of the building envelope is not correlated. The authors discuss these results in relation to social practices, material arrangements, and needs (comfort).

Studies aiming to understand specific occupant behaviors explained some of the variances in behavioral patterns by applying psychological or social factors. For instance, D'Oca et al. [152] found motivational

Table 3
Overview of studies applying different behavioral theories to explain occupant windows opening and ventilation behavior (abbreviation definitions of theories are listed below the table). Some of the identified studies only investigated specific constructs without specifying a theory (identified by '-' under the Theory column).

Manuscript	Theory	Constructs	Analysis	Method	Sample size	Building type	Country
Matthies et al. [57]	NAM (modified)	Awareness of consequences, personal norms, and lower cost of behavior	ANOVA	Experimental design	15 buildings/2041 participants (university staff)	University buildings	North Rhine-Westphalia, Germany
Galvin, R., [150]	-	Applying the framework of SPT*	Descriptive	Observation + structured interviews	401 observed + 50 interviews in 27 houses	Residential	Germany
Schweiker et al. [148]	-	Personality traits and element of SCgT*	Mixed effect logistic regression	Experimental lab study	65	Office	Germany
Wolff et al. [145]	-	Elements of SPT	Descriptive for ventilation behavior, ordinal least square regression for energy consumption	Semi-standardized interviews	80	Residential	Germany
Al-Marri et al. [79]	SDT; Maslow's Hierarchy of Needs	Awareness of need for enhancing sustainability for window opening	Descriptive	Surveys: laymen; Interviews: with experts	Survey 410, interviews 11	Residential	Qatar
Ornaghi et al. [147]	-	Elements of Theory of Normative Conduct, economic motivations & social norms	Regression	Observation from outside	5 buildings, 185 offices	Office	United Kingdom
Hansen et al. [149]	-	Social practices	Regression	Combined survey and administrative data on occupants	1216	Residential	Denmark
DellaValle et al. [151]	-	Elements of behavioral economic theories and SPT	Ordered probit model	Survey	277	Social Housing	Italy
D'Oca et al. [152]	-	Testing the DNAS framework	Chi-square goodness-of-fit test/logistic regression/ descriptive	Survey	1160	Office	Italy

NAM – Norm Activation Model; **SPT** – Social Practice Theory; **DNAS** – Drivers, Needs, Actions, Systems; **SCgT** – Social Cognitive Theory; **SDT** – Self-Determination Theory.

drivers for window opening is frequently driven by the need for fresh air, while for window closing is driven by the indoor or outdoor temperature (e.g., too hot or cold) as well as to reduce the noise levels. Additional concepts that are addressed include attitudes towards sharing window control, subjective norms (whether respondents believed that co-workers expected them to share their window controls) and the negotiation of behaviors. Schweiker et al. [148] show that the prediction of the window opening is improved when adding psychological elements such as personality traits or self-efficacy, an element of Social Cognitive Theory, to the statistical analysis. Al-Marri et al. [79] applied self-determination and hierarchical needs theories to window opening behavior. They explained the high percentage (69%) of respondents who reported to never open the window when the air-conditioning is cooling the room with environmental values based on lack of knowledge of the inefficiency, opposed to the 6% who always kept the air-conditioning running with knowledge regarding the efficiency of the AC-system.

Overall, among the papers reviewed, Social Practice Theory is the most studied theory in understanding occupant window openings and ventilation behavior [145,149–151]. Other theories mentioned are the Norm Activation Model [57], Self-determination and Hierarchical Needs Theory [79], a synthesis of the Theory of Planned Behavior, the DNAS framework and the Social Cognitive Theory [152], and personality traits and Social Cognitive Theory [148]. At the same time, the level of theoretical approach varies between these studies. While D'Oca et al. [152] and Matthies et al. [57] strictly applied the theory from the beginning of the experimental design, most papers use elements from theories for their experimental design; for instance, Ornaghi et al. [147] only referred to theoretical aspects of their work in the introduction and discussion sections of the paper.

4.2.2. Methodological approaches

As shown in Table 3, methodological approaches show a large variety, ranging from structured or semi-standardized interviews, questionnaires, over quasi-experimental, and experimental studies, to pure observational studies. Several studies combine more than one method towards mixed methods approaches [57,79,148–150]. Five of the nine studies were conducted in residential buildings [79,145,149–151]. Only one study was not located in Europe, but in Qatar [79]. Sample sizes varied largely, but mainly according to the methodological approach. Smallest sample sizes with 11 or 27 participants were related to interviews, the most time-consuming approach for the researcher. The larger sample sizes of 1216 or 2041 participants had questionnaire studies. A similar variety exists in the applied analysis methods. The methods range from studies with purely descriptive analyses related to window opening [79,150,152] to all other studies including statistical analysis such as varieties of regression analyses [145,147–149,151].

4.2.3. Discussion and identified gaps

Overall, a limited number of studies have examined different behavioral theories and predictors in understanding occupant window openings and ventilation behavior. In general, there are a few studies that have combined data from surveys and interviews with data from naturalistic studies; thereby, many of the identified studies have neglected the influence of environmental factors such as the indoor and outdoor temperature or indoor air quality on the window opening or closing behavior. Additionally, studies need to be better designed by focusing on a specific behavioral theory. Commonly, within the identified studies, the authors did not specifically focus on one theory but different constructs from one or multiple theories without a systematic approach in selecting these constructs. Additionally, in some cases, the relationship between experimental design and specific theories or constructs were not clearly explained. Furthermore, among the identified studies, as shown in Table 3, eight out of the nine studies were conducted in western Europe and one study was conducted in the Middle East; it is very important for future studies to be conducted in different geographical locations as different climate and cultural differences may impact the window opening or closing behaviors.

4.3. Interactions with lighting and shading systems

Lighting and shading systems are mainly utilized to provide visual comfort within the built environment. However, these systems, especially shading systems, can also affect the indoor temperature. There are a limited number of the reviewed studies (n = 7) that have explicitly applied behavioral theories (or specific constructs/elements) to investigate human interaction with lighting and shading systems [32,38,57,79,84,96,126]. Table 4 provides an overview of these studies. All of the studies mentioned the energy performance aspect of occupant interaction with lighting systems. One study also included the effects of shading interactions and climate on thermal comfort [38]. It is important to note that a number of identified papers evaluated how different behavioral theories can explain occupant interaction with lighting/shading systems in combination with other building systems; those papers are further discussed in section 4.6.

4.3.1. Theoretical approaches and general findings

The Theory of Planned Behavior (TPB) and the related theories branching from TPB (Theory of Reasoned Action [38] or modified version of TPB with the addition of habits [32]) are the most prevalent theories applied to explain lighting and shading interaction within the reviewed literature. Other mentioned theories include a modified version of the Norm Activation Model [57], Goal Framing Theory [84], Hierarchical Theory of Needs and Self Determination Theory [79], the Motivation Opportunity Ability framework [96], and Observe, Orient, Decide, and Act (OODA) Loop [38]. Applications of behavioral economics theories are also found; however, they are limited to Game Theory and Discrete Choice Theory [126].

Lo et al. [32] identified that TPB can fit the data well in order to explain pro-environmental behaviors in relation to lighting. The authors indicated that habit was a stronger predictor of light switching behaviors, in comparison to intentions. The authors also determined that the effects of habits on light switching behaviors varied across different organizations. The authors concluded that social-cognitive factors and habits were mostly significant predictors of intention, while attitude was not the strongest predictor of intentions. Specifically, they indicated that when relevant social norms are salient, perceived norms play a more prominent role. Perceived autonomy also did not heavily influence simple, daily energy-saving behaviors. The number of people sharing a space, the less inclined one is to switch lights off when no one is present, suggesting that shared responsibility on a certain behavior may be affected by other occupants' presence (in comparison to switching off monitor or printing behaviors). Moreover, the extended TPB model did not fully account for organizational differences in light switching behaviors, suggesting that the influence of social-cognitive factors on intention appears to be stable regardless of different organizational contexts [32]. Findings from Lo et al. [32] have multiple implications for behavior change interventions: (1) the relative influence of habit and intention on office energy-saving behaviors are the most important variable between contexts and should always be determined before implementation of interventions in organizational settings; (2) social-cognitive factors are more likely to be generalizable between contexts, allowing for standardization of interventions.

Lee and Malkawi [38] incorporated beliefs (from the Theory of Reasoned Action) in a simulation framework using an agent-based approach. Their approach to decision-making processes in an experimental simulation framework, where each behavior starts with initial behavior belief values but is subject to change throughout the simulation cycle based on their comfort level. Results of their simulations showed that in a hot climate, blinds are effective for energy performance and comfort. In a hot climate, solar radiation was more important than air movement for effective control of both comfort and energy performance. In contrast, for a cold climate, the controlling of air movement became

Table 4
Overview of studies applying different behavioral theories to explain occupant lighting and shading behavior (abbreviation definitions of theories are listed below the table). Some of the identified studies only investigated specific constructs without specifying a theory (identified by '-' under the Theory column).

Manuscript	Theory	Constructs	Method	Analysis	Sample size	Building type	Country
Matthies et al. [57]	NAM (modified)	Awareness of consequences, personal norms, and lower cost of behavior	Survey + Experimental design	two-way ANOVA analysis on behavioral change	15 buildings/ 2041 participants (university staff)	University buildings	North Rhine-Westphalia, Germany
Lo et al. [32]	TPB	Other constructs were added such as habit and organizational differences (type and number of mates) and familiar social norms.	Survey	Confirmatory factor analysis (CFA); Structural equation modeling (SEM)	Company ZH 1000; University LB 700; Company LB 450; NGO ZH 350	Non-residential (companies and university office building)	Netherlands Dutch provinces Zuid-Holland (ZH) and Limburg (LB)
Lee & Malkawi, [38]	TRA; OODA	Behaviors are associated with specific beliefs (behavioral, control, normative) values (from TRA) in terms of cost function	Simulations	Agent-based modeling	-	Non-residential	Phoenix, San Francisco USA; Calgary, Canada
Da Li et al. [96]	MOA	Motivation level for energy savings + for turning off lights	Survey	Reliability analysis; K-means clustering analysis; Structural equation modeling	177 occupants (one 32 story building)	Non-residential (university office buildings)	Chicago, United States
Al-Marri et al. [79]	SDT, Hierarchical theory of needs	Awareness of need for enhancing sustainability (NER) for switching off lights	Survey; Interview	Multiple regression analysis; Interviews: coding process	410 sample + 11 interviews	Residential	Qatar
Gerhardsson [84]	Goal Framing Theory	Hedonic goals and normative goals within NER.	Mixed-methods approach: structured interviews with open-ended questions and a survey with multiple-choice questions.	Surveys: descriptive statistics Interviews: Thematic analysis; Formal coding	Surveys 536 Interviews 12	Residential	Sweden
Konstantakopoulos et al. [126]	Game Theory; Discrete Choice Theory	Gamification, feedback, competition	Experimental design	*t*-tests	72 rooms	Residential (dormitory)	Nanyang, Singapore

NAM – Norm Activation Model; **TPB** – Theory of Planned Behavior; **TRA** –Theory of Reasoned Action; **OODA** – Observe, Orient, Decide, and Act; **MOA** – Motivation Opportunity Ability; **SDT** – Self-Determination Theory.

more effective than controlling solar radiation.

The work of Li et al. [96] shows that the motivation level of occupants can affect energy-saving behaviors. Therefore, occupancy interventions can focus on improving occupants' motivation level to induce energy-saving lighting and shading interactions in occupants (i.e. turning off lights when leaving). According to their study, occupancy interventions can be utilized to (1) provide thermal comfort conditions for occupants, (2) utilize peer-pressure among coworkers, and (3) promote their motivation level of occupants by improving self-assessed knowledge of occupants on energy conservation. This study also found distributing information about energy consumption facts and reduction guidelines is not effective in influencing occupants. On the contrary, feedback and peer-comparison are among the most effective education methods on promoting energy conservation behaviors among the occupants [96].

The results of Al-Marri et al. [79] study indicate an overwhelming support for energy-saving among the participants, which is inconsistent with their behavior and habits; Al-Marri et al. [79] indicate that despite their knowledge of environmental risks and awareness of consequences, only a small group of the participants demonstrated energy-saving behaviors. Regarding lighting systems, 60% of the participants reported that they always turned off the lights if they were the last person to leave the room. Results from interviews are consistent with the theory of self-determination, indicating the lack of economic consequences (extrinsic motives) has contributed to excessive energy consumption behavior. Consequently, an option that encourages changed behavior through intrinsic motivation needs to be explored. In this regard, Al-Marri et al. [79] identified that education, public engagement, and awareness are the best options for domestic energy conservation in Qatar.

Gerhardsson et al. [84] found that two types of goals from the Goal Framing Theory (hedonic and normative goals) can guide certain lighting interaction behaviors in single-family houses, such as the purchase of energy-efficient lamps. Changes in lighting purchase behavior (use of energy-efficient lamp technology) did not significantly correlate with changes in lighting interaction habits. In this study, lighting interactions (turning off the lights in non-occupied rooms) were not directly assessed by theoretical constructs from the mentioned theory, but rather viewed as a consequence of other lighting behaviors (e.g. changing lighting technology) driven by specific motives or goals.

Matthies et al. [57] conducted a study using the Modified Norm Activation Model on the reduction potential of psychological interventions on energy consumption behavior in public (non-residential) buildings. The study collected data using electricity-consumption and heat-consumption metering, behavioral monitoring, as well as self-reported behaviors ($n = 2034$). A part of the study focused on the effects of the intervention (energy saving campaign) on the treatment group vs. the control group related to electricity and heat consumption, and window position data, which did not specifically include lighting systems. The surveys of self-reported adoption of energy-saving tips included lighting behavior and only utilized the post-test data of the treatment sample. The analysis of the adoption of energy-saving tips was based on a sub-sample of the treatment group ($n = 155$). In the post-test questionnaire of the treatment group, participants were asked to indicate which energy-saving behavior they adopted as the result of interventions (campaign). On average 2.8 behaviors were selected out of the available 12 options. The most frequently selected behavior included switching off lights when leaving the office (48%) and when daylight is adequate (43%). Of the most frequent adopted energy-saving behaviors, switching off lights was not among the ‘intensely-promoted’ behaviors of the campaign. Behavioral changes were analyzed by two-way ANOVA using (pre-test vs post-test) and group membership (treatment vs. control) as the factors. The behavioral change analysis was based on a subsample of the surveys with complete dependent measures of self-reported behavior for both pre-test and post-test measurements ($n = 139$). ANOVA analysis found a significant interaction effect concerning switching off the lights during the short absence of the participants ($F = 4.65$, $p < 0.05$).

Konstantakopoulos et al. [126] used Game Theory and Discrete Choice Theory to study the effectiveness of a non-cooperative social game on energy consumption. The lighting behavior data was collected through the Internet of Things (IoT) devices. The social game study was performed at a college dorm ($n = 72$ single-room dorms) for two consecutive semesters. Each single-room-dorm included two IoT devices, collecting data from HVAC systems, fans, ceiling lights, and desk lamps. An auto-encoder generative model was also created based on the sensor readings. The auto-encoder model serves as a useful tool in simulating and mimicking the behavior of occupants [126].

4.3.2. Methodological approaches

Within the few identified studies, over half of them were conducted in non-residential settings (three were conducted in residential buildings). Locations where these studies were conducted included, the United States [38,96], Singapore [126], Netherlands [32], Qatar [79], Germany [57], and Sweden [84]. Studies were not strictly limited to occupant interaction with lighting/shading systems, as three studies included other building systems (e.g. fan use). However, all of the mentioned studies specifically included measures of occupant interactions with lighting and shading systems. The majority ($n = 5$) of studies utilized the survey method to collect participant-related information. Two studies included interviews and one study was performed based on simulations. Except for the simulation study, samples were usually larger than 150. The smallest sample size was 72 (college students - single room dorms). The study by Lo et al. [32] contained the largest sample size of 2500 participants.

4.3.3. Discussion and identified gaps

Overall, the studies showed that energy saving related to lighting behavior is already prevalent among the participants and achievable even without serious intervention and campaigning [57,79]. This is in part explainable by the prevalence of energy-saving lighting habits, such as turning off the lights upon departure (as the last person) [32,79]. The evidence also supported the effectiveness of interventions on lighting and shading interactions [32,96].

One major limitation of the studies was the lack of proper design of studies. For instance, the study by Ref. [107] did not include a control group. Additionally, studies by Refs. [79,84] did not report or measure the influences of theoretical constructs on interactions with lighting and shading systems. Lee et al. [152] also based their study on simulations that requires further verification using real-world data. Lastly, as it is shown in Table 4, there is a need for more studies to be conducted in different countries as various geographical locations and cultural differences may significantly influence the lighting and shading behaviors.

4.4. Occupant electronic devices and appliance use

Ten studies were identified that explicitly used behavioral theories to study occupant interactions with electronic devices and appliances within residential and non-residential buildings. The specific theories studied within previous literature include first and foremost the Theory of Planned Behavior (TPB) or a derivative of it, but also Social Practice Theory (SPT), Social Cognitive Theory (SCgT), the Norm Activation Model (NAM), or Goal Framing Theory. Notably, two main categories of studies emerged, with one group of studies directly testing the applicability and explanatory power of these theories, and the other using theoretical knowledge to guide the development of energy-saving interventions.

4.4.1. Theoretical approaches and general findings

By applying TPB, among other energy-saving objectives, Greaves et al. [34] studied the intention to switch off the work computer (PC) through a questionnaire within an organization in the United Kingdom (UK). The TPB constructs were able to explain 61% of the variance in PC switching off intentions, and antecedents for the TPB constructs were analyzed. In a similar vein, Tetlow et al. [35] looked at the energy consumption at individual workstations in two open-plan offices in the UK from the perspective of the TPB, supplementing it with the habit construct. The latter construct was the only one being significantly associated with energy consumption, explaining about 11% of the variance in energy consumption as measured with plug-in monitors. A similar research model (TPB plus habit) has been applied by Lo et al. [32], analyzing its predictive power regarding self-reported energy-saving behaviors (i.e., printing smaller, not printing emails, switching off monitors, switching off lights). The survey was conducted in four organizations in the Netherlands, and depending on the type of analysis, between 600 and 900 responses have been analyzed. Galvin and Gubernat [106] analyzed the rebound effect of a university research group setting and applied the Social Practice Theory. By taking this collective-oriented approach, much higher rebound effects were identified than compared to an individual-oriented perspective. As main drivers for this development, specialization of ITC-branches offering services within an organization (termed a “bulge”) and the availability of data analysis services (“more is never enough”) were identified. Debnath et al. [107] also applied the Social Practice Theory (SPT) to investigate appliance ownership in 1,224 households that moved in to slum rehabilitation housing in Mumbai. The SPT helped to identify and shift the focus on non-income factors that influence appliance ownership and ultimately electricity consumption, i.e., the built environment, household practices, and appliance characteristics.

The intervention by Murtagh et al. [153], conducted in a university setting, tracked the energy use of 83 workers while providing feedback over an 18-week period. A reduction of energy usage could be observed during the later stage of the monitoring phase, but no significant associations of individual variables (values regarding biosphere, attitude towards technology) and energy reduction were found. A German university setting with more than 2,000 staff members was selected by Matthies et al. [57], who tested the efficacy of an intervention based on the Norm Activation Model (NAM) with a quasi-experimental approach. The energy savings observed amounted to 43% (electricity) and 10% (heating) of the calculated maximum saving potential. Besides an impressive sample size, this study features an integrative analysis of consumption data (heat and electricity), behavioral monitoring (window opening), self-reports, and simulation of potential savings, all conducted within a quasi-experimental pre-post control group design. Mulville et al. [54] were able to achieve an average reduction in energy consumption of 18.8% by providing three types of feedback to 39 office workers (presumably in the UK). Similar to the study by Tetlow et al. [35] (cited above), pre- and post-intervention surveys revealed no significant changes regarding attitude or social norms, leading to the conclusion that habit changes are the drivers of energy-saving efforts. The study by Mulville and colleagues stands out due to its extensive pre- and post-intervention monitoring phases, which lasted 100 days each. Cornelius et al. [68] provide an example of how to involve young people in energy saving and greenhouse gas reduction. The intervention for 165 high school students involved five lessons over a five-week period and was founded on the Social Cognitive Theory. Education on climate-relevant issues was illustrated with the help of balloons depicting the amount of CO_2 emissions caused. The index measuring conservation behavior increased by 26.5% based on self-report, with the greatest changes occurring in hang drying clothes as well as switching off appliances.

Rewards, granted publicly or privately, rest at the intersection of psychologically and economically oriented theories used to achieve behavioral changes. Within this integrative approach, Handgraaf et al. [71] investigated the effect of publicly and privately awarded social and financial rewards on computer energy saving. The experimental study relied on the Social Comparison Theory and the Goal Framing Theory, conducted with 83 workers of a Dutch consultancy firm. As expected by the authors, social rewards generally had a stronger positive effect on energy conservation than the monetary rewards, and public feedback had a stronger effect than feedback provided privately. Workers receiving a public/social reward revealed an average conservation of 6.4%, while private monetary rewards were shown to be counter-productively, leading to an increase in electricity consumption of 3.2%. It is noteworthy that eight weeks after cessation of rewarding, people in the social reward conditions were still conserving energy, showing the enduring effect of this intervention.

4.4.2. Methodological approaches

In order to test behavioral theories in terms of their explanatory power, mainly questionnaire surveys based on self-reported use of electronic devices and appliances have been employed (n = 4), and the majority of participants were studied in non-residential settings such as offices and universities. More studies rely on theoretically based interventions in order to achieve energy savings. These intervention studies (n = 5) were conducted with similar target populations, although one of these studies targeted high school students. Geographically, most of the studies have been conducted in Europe, more specifically the Netherlands, Germany, and the UK. Table 5 provides a brief overview of the studies that applied behavioral theories to explain occupant behaviors using different appliance and electronic devices.

4.4.3. Discussion and identified gaps

In essence, helpful insights have been generated by applying behavioral theories in describing, explaining, and changing our interaction with electronic devices and appliances. The predominant model appears to be the combination of TPB and Habits (which corresponds to Triandis' TIB [52]), and it might prove beneficial if future studies applied this (or another) theory-based, coherent model instead of occasionally incorporating scattered constructs that are operationalized with only one or two questionnaire items. Those studies applying the TPB/TIB framework show that behavioral changes may be due largely to changes in habit, while social norms and attitudes remained more unaffected.

Due to the complexity and multi-determinacy of human behavior, the reviewed papers occasionally led to "mixed" results. One issue giving rise to this may be the reliance on self-reported intentions to save energy versus. the actual (measured) savings, a situation already described as the Attitude-Behavior-Gap. Of course, there are trade-offs between sample size and feasibility of monitoring, but due to devices getting cheaper and smaller, this issue should be alleviated in the near future. Extensive monitoring always increases the study efforts, but especially intervention studies benefit from longer baseline measurements and follow up observation periods.

4.5. Occupant domestic hot water use

Few papers have explicitly analyzed domestic hot water use in isolation. We identified only four studies in this category, although it should also be noted hot water use was sometimes combined with

Table 5
Overview of studies applying different behavioral theories to explain occupant appliance and electronic device behaviors (abbreviation definitions of theories are listed below the table). Some of the identified studies only investigated specific constructs without specifying a theory (identified by '-' under the Theory column).

Manuscript	Theory	Constructs	Method	Analysis	Sample size	Building type	Country
Psychological							
Matthies et al. [57]	NAM (modified)	Awareness of consequences, personal norms, and lower cost of behavior	Intervention study, Experimental design	ANOVA	15 buildings/2041 participants (university staff)	University buildings	North Rhine-Westphalia, Germany
Greaves et al. [34]	TPB	Intentions	Survey	Path analysis	449	Office	United Kingdom
Murtagh et al. [153]	-	Attitude, pro-env. values, env. identity	Intervention study; Survey, electricity consumption data, focus groups	Linear regression	83 responders (18 weeks)	Office (University campus)	United Kingdom
Cornelius et al. [68]	SCgT	Energy-/GHG-related behaviors, sustainability attitudes; perceived self-efficacy; knowledge	Intervention study, baseline survey + lessons for the treatment group	Hierarchical linear modeling; ANCOVA	165 high school students in six classrooms	High school	Palo Alto, United States
Lo et al. [32]	TPB	Habit, Organizational context	Survey	Structural equation modeling	4 organization, 600 - 900 responses (varied based on analysis)	Office (2), University (1), NGO (1)	The Netherlands
Tetlow et al. [35]	TPB	Habit	Survey	Multiple linear regression	81	Office	United Kingdom
Galvin and Gubernat [106]	SPT	Rebound effect	Case Study	Calculation of Rebound effect (two-year comparison)	Research cluster, 75/187 workers (2008/2015)	Office (University research cluster	Germany
Mulville et al. [54]	TIB	feedback, goal setting, education	Intervention study, survey	ANOVA, correlation	39 workers	Open-plan office	United Kingdom
Debnath et al. [107]	SPT	Household practices, appliance characteristics, built environment	Survey	Structural equation modeling	1224 households	Residential	Mumbai, India
Integrated (Psychology & Economics)							
Handgraaf et al. [71]	SCmT; Goal Framing	Motivation to improve energy conservation, positive emotions	Intervention study, quasi-experimental pre-post control group design	ANOVA	83 responders	Office	The Netherlands

NAM – Norm Activation Model; **TPB** – Theory of Planned Behavior; **SPT** – Social Practice Theory; **SCgT** – Social Cognitive Theory; **TIB** – Theory of Interpersonal Behavior; **SCmT** – Social Comparison Theory.

investigation of energy conservation behaviors generally, and thus reviewed in the following section regarding mixed systems (Section 4.6).

4.5.1. Theoretical and general findings

Each of the research papers investigating domestic hot water drew upon different theoretical frameworks to guide their analysis, all of which were from the field of psychology. These theories included Construal Level Theory [74], Norm Activation Theory [56], the Theory of Planned Behavior [36], and the Drivers, Needs, Actions, Systems (DNAs) framework [100]. Given the different theoretical approaches used by these four studies, their results spoke to different aspects of hot water use. For example, Griffioen et al. [74] showed that an intervention designed according to Construal Level Theory helped all experimental groups reduce water use over a six-week period. The findings indicated that interventions which align their level of construal were marginally more effective at reducing water use than those that did not. Alternatively, the work by Haines et al. [100] developed four typologies of hot water use in the residential sector, suggesting residents have distinctly different ways of interacting with their hot water systems. Such typologies could help target programs to alter the use and/or adoption of specific household systems. Fielding et al. [36] uses the Theory of Planned Behavior to understand water use and claims that the psychological constructs such as attitudes, subjective norm, and perceived behavior control can be more useful in predicting household-level water consumption, compared to the application of theoretical constructs to individuals. In their study, the authors found that sociodemographic, psychosocial, behavioral and infrastructure variables play a significant role in determining household water use. Finally, the work by Refs. [56] supports the wider literature applying the Norm Activation Model to building systems, showing that personal norms explained 5% of the variance in occupant time spent showering and 18% of the variance in intentions to save energy.

4.5.2. Methodological approaches

With regard to the methodological approaches used, three of the studies relied on survey responses and self-reported behavior change [36,56,74], one of which was deployed during an experimental field study [74]. The other study used in-depth, semi-structured interviews to understand and develop a typology regarding water heating practices [100]. Three studies focused on the residential sector, while the fourth researched university housing, with sample sizes ranging between 35 households to over 1000 individuals. Both qualitative and statistical modeling approaches used to evaluate the results. Two of the studies were conducted in the Netherlands, one in the United Kingdom, and one study in Australia. Table 6 provides an overview of these studies.

4.5.3. Discussion and identified gaps

Given the limited number of studies our review returned, we suggest more research is needed in this space to better understand the drivers of hot water heating related behaviors. As four different theories of behavior were applied across the studies, the results show the ability for different frameworks to produce diverse insights into behavior associated with a single building system. At the same time, the lack of consistency with which theories have been applied makes it difficult to distill gaps in the literature overall or draw consistent conclusions about the most significant drivers of hot water use. With the exception of the study by Fielding et al. [36], each of the papers reviewed uses a relatively small sample size potentially making it difficult to generalize the findings across populations. Further, as literature becomes more prevalent on this topic, researchers should aim to conduct studies in different geographical locations as cultural and economic factors may significantly impact occupant hot water behavior.

4.6. Occupant mixed systems use

Our review identified an extensive number of studies in the mixed systems category that had either focused on (1) general energy conservation behaviors in buildings (i.e. intentions to reduce energy consumption) without describing any specific building system or (2) occupant interactions with multiple systems and reporting behaviors and interactions as one aggregated metric. This section constituted 53 papers. Since a large number of papers focused on mixed systems, we divided this section into three subsections each focusing on a distinct discipline: psychological (Section 4.6.1), sociological (Section 4.6.2), and economic theories (Section 4.6.3). Section 4.6.4 provides a cohesive discussion and the identified gaps related to these three subsections.

4.6.1. Psychological theories

A large number of papers analyzed mixed system use by applying different psychological theories. Specifically, psychological theories account for 39 out of the 53 papers identified for this area. In this section, we provide an overview of these studies.

4.6.1.1. Theoretical approaches and general findings. As shown in Tables 1 and 7, within the papers reviewed, the Theory of Planned Behavior (16/39 papers), the Value Belief Norm Theory (5/39), and the Norm Activation Model (5/39) have been widely implemented to understand energy conservation behaviors in buildings. In addition, the Motivation Opportunity Ability Theory and the Stage Model of Self-regulated Behavior Change were cited by two papers each. While these five theoretical frameworks were referenced by more than one study, many others in our sample were cited by only one, including the

Table 6
Overview of the studies applying different behavioral theories to explain domestic hot water behavior (abbreviation definitions of theories are listed below the table). Some of the identified studies only investigated specific constructs without specifying a theory (identified by '-' under the Theory column).

Manuscript	Theory	Constructs	Method	Analysis	Sample size	Building type	Country
Fielding et al. [36]	TPB	Intentions, attitudes, subjective norms, perceived behavioral control	Survey + water consumption data	Quantitative, Sequential regression	1008	Residential	Queensland, Australia
Van der Werff and Steg [56]	NAM	Awareness of Consequences, Outcome Efficacy, Personal Norm, Normative factors	Door-to-door survey	Regression analysis with bootstrapping intervals	468 respondents	Residential	Netherlands
Griffioen et al. [74]	CLT	Construal Level, Social Distance	Experimental field study	2 (Construal Level: low vs. high) × 2 (Social Distance: low vs. high) plus control condition in a between-subjects comparison; ANOVAS for within subject comparison	197	Residential (one-person student housing apartments)	Netherlands
Haines et al. [100]	DNAS	Drivers, needs, and actions	Semi-structured interviews	Applied the DNAS framework	35 households	Residential	UK, East Midlands

TPB – Theory of Planned Behavior; **NAM** – Norm Activation Model; **DNAS** – Drivers, Needs, Actions, Systems; **CLT** – Construal Level Theory.

Table 7
Overview of studies explaining energy conservation and mixed system behaviors by applying different psychological theories (abbreviation definitions of theories are listed below the table). Some of the identified studies only investigated specific constructs without specifying a theory (identified by '-' under the Theory column).

Manuscript	Theory	Constructs	Method	Analysis	Sample size	Building type	Country
Harland et al. [39]	TPB	Personal norms, perceived behavioral control, subjective norms, and attitudes	Survey	Intercorrelation stats, hierarchical regression	305	Residential	Denmark
Abrahamse et al. [162]	-	Group and individual goals, tailored feedback	Survey	Repeated measures ANOVA	189 households	Residential	Groningen, Netherlands
Scherbaum et al. [60]	VBN	Environmental view, personal norms, intentions, behaviors	Survey	ANOVAs, Structural equation analysis	154 employees	Office (university)	Midwest, United States
Abrahamse and Steg [40]	TPB; NAM	Attitude, perceived behavioral control, personal norm, awareness of consequences, ascription of responsibility	Survey	Hierarchical regression model	314	Residential	Groningen, Netherlands
Gill et al. [41]	TPB	Attitude, subjective norm, perceived behavioral control	Surveys, interviews	Content analysis	11 households (interviews), 18 (surveys)	Residential	United Kingdom
Abrahamse and Steg [42]	TPB, VBN	Attitudes, perceived possibilities, environmental values, beliefs and norms	Survey + data on annual gas and electricity consumption	Hierarchical regression model with principal component analysis	199	Residential	Groningen, Netherlands
Matthies et al. [57]	NAM (modified)	Awareness of consequences, personal norms, and lower cost of behavior	Experimental design	ANOVA	15 buildings/ 2041 participants (university staff)	University buildings	North Rhine-Westphalia, Germany
Carrico and Riemer [163]	-	Conservation behavior, perceived descriptive and injunctive norms, collective outcome expectancy beliefs, and goal attractiveness	Electricity data, surveys	ANOVA	24 buildings, 352 participants (staff, faculty, and graduate students)	University buildings	South of United States
Menzes et al. [51]	TPB	Attitude, subjective norm, perceived behavioral control	Electricity data for lighting and appliances + survey	Regression analysis	432 survey respondents + electricity consumption for 27 zones	Office building	London, United Kingdom
Huebner et al. [161]	-	Habits, intentions	Surveys; Interviews; meter readings	ANOVA, regression, qualitative analysis	41 households	Residential (social housing)	United Kingdom
Webb et al. [80]	SDT; Goal-directed behavior	Attitude, emotions, subjective norm, perceived behavior control, desires, intentions	Survey	Structural equation analysis	200 participants	Residential	Australia
Zhang, Wang, & Zhou [58]	NAM	Awareness of consequences, ascription of responsibility, personal norm, organizational electricity-saving climate	Survey	Partial least squares structural equation analysis	273	Office	Beijing, China
Cornelius et al. [68]	SCgT	Energy- and GHG-related behaviors, sustainability attitudes; perceived self-efficacy; knowledge about behaviors that contribute to climate change	Baseline survey + lessons for the treatment group	Hierarchical linear modeling; ANCOVA	165 high school students in six classrooms	High school	Palo Alto, United States
Lee and Malkawi [38]	TPB	Attitudes, subjective norms, perceived behavioral control	Experimental simulation	Dynamic simulation (Energy Plus)	-	Non-residential	USA: Philadelphia (PA), Phoenix (AZ), San Francisco (CA) Calgary (AB, Canada),
Octav-Ionut [43]	TPB; NAM	Attitude, awareness of the consequences, subjective norms, perceived behavioral control, intentions	Survey	Structural equation analysis	133	Residential	Romania
Guerreiro et al. [50]	TRA, TAM	Attitude, subjective norm, perceived usefulness, perceived ease of use, risk perception, procedural justice	Survey	Qualitative content analysis, logistic regression	515 participants	Residential	Évora, Portugal
Dixon et al. [44]	TPB	Descriptive norms, injunctive norms, perceived behavioral control, attitudes, intentions, sense of community	Survey	Hierarchical regression model	2,919 faculty, staff, graduate students	University campus	Ithaca, United States
Dixon et al. [156]	TPB		Survey + energy consumption data	Hierarchical regression model		Mixed-use buildings with a	Ithaca, Geneva, United States

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Table 7 (*continued*)

Manuscript	Theory	Constructs	Method	Analysis	Sample size	Building type	Country
		Descriptive norms, injunctive norms, perceived behavioral control, attitudes, intentions			Study 1: n = 2112; Study 2: n = 1601	combination of research, teaching, and academic space	
Huebner et al. [160]	-	Climate change beliefs on energy consumption	Survey	Ordinary least squares regression	924 households	Residential	United Kingdom
Nachreiner et al. [76]	Self-regulated Behavior Change	Norms (social/personal), emotions, perceived responsibility, perceived consequences, attitudes and perceived behavioral control, self-efficacy)	Access to a smart meter web portal	Qualitative content analysis	-	Residential	Germany
Langevin et al. (2016) [39]	PCT	Personal control opportunities/perception of control	Simulation	Agent-based modeling	-	Office (medium size)	Philadelphia, Los Angeles, Chicago, San Francisco, Houston, United States
Wells et al. [154]	-	Attitudes to water and energy savings	Survey	Structural equation modeling with partial least squares	5 hotels, 447 responders (hotel staff)	Hotels	Iran
van der Werff and Steg [61]	VBN	Values, environmental self-identity, problem awareness, outcome efficacy, personal norms, interest, and participation	Survey	Regression	203	Residential	Amersfoort, Netherlands
Hewitt et al. [62]	VBN	Values, beliefs, personal norms	Survey	Structural equation modeling	161 apartment units	Residential	Northeast, United States
Zierler et al. [45]	TPB; TIB	Energy self-efficacy, behavioral intention, benefit evaluation (attitude), goal flexibility	Survey	Structural equation analysis	628	Non-residential	United Kingdom
Leygue et al. [86]	FAT	Commitment to one's organization, organizational identification, environmental concerns	Survey	Regression	Study 1: n = 293, Study 2: n = 94	University buildings	United Kingdom
Chen et al. [48]	TPB	Attitudes, subjective norms, perceived behavioral control	Survey	Hierarchical regression model with principal component analysis	248 MTurk participants	Residential	United States
Li et al. [96]	MOA	Opportunity (control systems, expose to information, expose to peer pressure), motivation, ability (perceived energy conservation knowledge)	Survey	Structural equation modeling, k-means clustering	177 occupants	Office	Chicago, United States
Azar & Al Ansari [63]	VBN	Norms, beliefs, attitudes, and actions	Survey	Linear regression	227	University campus	Abu Dhabi, United Arab Emirates
Gao et al. [46]	TPB	Attitude; Perceived behavioral control; Subjective norm; Descriptive norm; personal moral norm	Survey	Structural equation analysis	52 companies, 320 responders	Office	Shanghai, Hefei, Luan, China
Erell et al. [140]	-	Environmental awareness, attitude to environmental issues	Survey	Experimental design	114 households	Residential	Jerusalem and Nesher, Israel
Nie et al. [47]	TPB	Attitude, subjective norm, perceived behavior control	Survey	Structural equation analysis	396 households	Residential	Changchun, China
Mack et al. [77]	Self-regulated Behavioral Change	Norms (social/personal), emotions, perceived responsibility, perceived consequences, attitudes and perceived behavioral control, self-efficacy	Survey; energy consumption and user web portal usage data	ANOVA analysis, k-means cluster analysis	86	Residential	Heidelberg, Germany
Tang et al. [158]	Stimulus-organism-Response Theory	Descriptive norms, Social pressure, intentions, personal responsibility, organizational goal	Survey	Structural equation analysis	249 SOJUMP participants	Office building	China
Murtagh et al. [94]	Protection Motivation Theory (PMT)	Threat appraisal, coping appraisal, overheating experience, knowledge of precautionary actions, protection motivation	Survey	Logistic regression	1007	Residential (apartment, townhouse, duplex)	South and midlands, United Kingdom
Guerra-Santin et al. [157]	-	Attitudes, Thermal comfort preference, Household daily practices	Interview + Environmental data (e.g. lighting, thermal)	Mixed Methods, Data mining & interpretation	270 participant responses	Residential	(Case studies) Netherlands, Spain

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Table 7 (*continued*)

Manuscript	Theory	Constructs	Method	Analysis	Sample size	Building type	Country
Lee et al. [155]	-	Attitude towards comfort, Perceived environment control, Awareness of energy saving, Neighbor relationship, Pride	Survey	*t*-test, ANOVA, Multiple Linear Regression	182 survey responses	Residential	South Korea
Obaidellah et al. [49]	TPB (modified - subjective norm taken out)	Attitudes toward energy saving, perceived behavioral control, intentions (mediator)	Survey	Partial Least Squares Structural Equation Modelling (SEM-PLS)	281 respondents	Office	Malaysia
Li et al. [37]	TPB; NAM; MOA	Attitude, awareness of consequence, ascription of responsibility, personal norms, accessibility to control, descriptive norm, organizational support, time availability, perceived behavioral control, actual knowledge	Survey	Path Model Analysis Structural equation modeling	612 Qualtrics responses	Office	United States

TPB – Theory of Planned Behavior; **VBN** – Value Belief Norm; **NAM** – Norm Activation Model; **SDT** – Self-Determination Theory; **SCgT** – Social Cognitive Theory; **TRA** – Theory of Reasoned Action; **TAM –** Technology Acceptance Model; **PCT** – Perceptual Control Theory; **TIB** – Theory of Interpersonal Behavior; **FAT** – Functional Attitude Theory; **MOA** – Motivation, Opportunity, Ability; **PMT** – Protection Motivation Theory. **SPT** – Social Practice Theory;; **TIB** – Theory of Interpersonal Behavior; **SCmT** – Social Comparison Theory.

Stimulus Organism Response Theory, Self-determination Theory, the Functional Attitude Theory, the Theory of Interpersonal Behavior, the Theory of Reasoned Action in combination with the Technology Acceptance Model, Social Cognitive Theory, Perceptual Control Theory, and Protection Motivation Theory. Table 7 provides an overview of these studies.

Across the studies and theoretical frameworks reviewed, a large majority supported the positive impact of attitudes, norms, and perceived control on the performance of energy conservation behaviors in buildings. For example, individuals' attitudes towards energy conservation have been found to positively influence intentions towards energy savings [40,42–49,56] in addition to self-reported energy-saving behaviors at home and at work [154,155]. Results from many studies in the sample revealed that occupants' perceived control positively influenced both intentions and behaviors around energy conservation [40,42–49,56,80,155–157].

In addition, several studies across theoretical disciplines investigated the role of normative influence on conservation behaviors. Subjective norms [43,44,47,48,50,56,80], personal norms [58], and peer pressure [96] were shown to positively influence intention to undertake and actually perform energy conservation behaviors. Personal norms were also identified to have a positive, significant influence on motivation for people to move to green buildings [62]; other factors such as environmental-personal norms and descriptive norms were also identified through self-reported surveys evaluating energy-conservation behaviors and intentions as a motivating factor for people to move to green buildings [46,56,60,156]. Tang et al. [158] also found that descriptive norms, organizational energy-saving climate, and media publicity (i.e., stimulus) had a significant direct and positive impact on employee's perceived energy-saving responsibility and social pressure (i.e., organism), and consequently on energy saving intentions (i.e., response).

Despite the strong validity and applicability of these factors, their relationship and predictive power clearly vary for different studies. For example, the study by Ref. [50] reported no significant effect of attitudes on energy conservation behavior; similarly, Gao et al. [46] and Hewitt et al. [62] showed insignificant effects of social and personal norms on energy conservation behaviors, respectively. Cornelius et al. [68] also concluded that self-efficacy, a concept similar to that of perceived control, can result in a positive influence on energy conservation, specifically for switching off appliances and other devices. Lastly, opportunities to control building and individual systems were shown to have mixed impacts on saving energy, office productivity, and thermal comfort [66]. The study by Refs. [155] showed that individual control systems can facilitate energy saving behavior.

In addition to the key factors discussed above, studies also reviewed the influence of other constructs such as the role of values, beliefs, and awareness of energy conservation behaviors. As with the other common factors, studies reported mixed impacts on behavior in buildings. For example, self-transcendence and biospheric values have a positive influence on energy savings [61,159] as did awareness of consequences on energy conservation behaviors and intentions [43,155]. However, van der Werff and Steg [56] did not find awareness of consequences having a significant effect on energy conservation behavior. Similarly, while Huebner et al. [160] found a positive relationship between beliefs about climate change and energy consumption, in another study, no significant effect was found between beliefs and energy-saving practices [161]. Furthermore, Webb et al. [80] concluded that negatively anticipated emotions were not significantly related to intentions, but positively anticipated emotions were significant predictors of them. In addition, a study by Lee et al. [155] found that energy saving intentions lead to higher satisfaction with environmental comfort and energy saving behavior.

A number of papers also sought to investigate the role of occupant motivation on behavior. For instance, Leygue et al. [86] found that different motivations and attitude functions determine intent to save energy at work. These findings highlight the relevance of integrating self-determined motivations as predictors of behaviors. Erell et al. [140] showed mixed results around the role of financial, environmental, and social motivations to impact heating and cooling related behaviors and energy consumption.

For certain studies, behavioral theories have been extended to understand other social-psychological variables, which may contribute as additional drivers to predict energy conservation intentions and behaviors and energy use. Examples of these are: bill consciousness and needs for warmness and coolness [48], sense of community [44], perceived usefulness and percentage of risk of the analyzed device [50], socio-demographic variables such as income, household size, age, gender, and climate zone [42,48,58], and the number of children in a household and occupants' education level [47].

Although psychological theories have been mostly applied at an individual level, in some studies they were applied to a household as a whole. A number of studies also focused on the role of feedback on reducing household energy consumption. For instance, the work of Nachreiner et al. [76] and Mack et al. [77] focused on the feedback information and impacts on energy savings potential by addressing all stages of behavioral change [76,77]. Several studies also showed that feedback in combination with other strategies such as goal setting [162] and peer education [163] could lead to between four and seven percent building energy reductions. The study by Guerra-Santin et al. [157] showed that household energy saving attitudes can impact energy conservation and heating use. They also found that occupant behavior in Spanish household was followed a very constant daily routine and habit patterns.

4.6.1.2. Methodological approaches. As shown in Table 7, just over half of the studies in this section were conducted in residential environments, while the remaining studies were done in office buildings. The main geographical locations that the identified studies were conducted included, the United States, the United Kingdom, Netherlands, China, other European countries (mainly Western Europe except one study), Australia, and Malaysia. Of the identified studies, almost all employed quantitative surveys. Interviews were employed as an additional method in two studies [41,161]. Furthermore, several studies reported evidence from field studies using the data from smart meter web portals [76,162] or classroom lessons as educational approach feedback to high school students [68]. Only two studies used simulation methods [38,66].

Most studies measured energy conservation intentions and self-reported energy-saving behaviors while fewer measured actual energy savings and other building systems, such as water consumption. Just under half of the studies were tested in sample sizes higher than 300. The applied analysis methods include descriptive analysis and varieties of statistical analysis, such as hierarchical regressions (7/39), structural equation models, sequential regression MANOVA, ANOVA, OLS regression analysis and qualitative content analysis.

Table 8
Overview of studies applying different sociological and economic theories to explain behaviors related to a set of systems (mixed systems) and/or energy conservation (abbreviation definitions of theories are listed below the table). Some of the identified studies only investigated specific constructs without specifying a theory (identified by '-' under the Theory column).

Manuscript	Theory	Constructs	Method	Analysis	Sample size	Building type	Country
Sociological							
Stephenson et al. [111]	Energy Cultures Framework	Norms, material culture, practices	Observation	Two-step cluster analysis	2400 households	Residential	New Zealand
Maréchal [117]	STS	Habits	Survey, Interview	Simple statistical analyses	109 (tenants and landlords), Survey: 200+ participants	Residential	Belgium
Gram_Hanssen [105]	SPT	Practices, know-how, and embodied habits, knowledge, engagement, technologies and material structures	Interview	Qualitative analysis	10 participants	Residential	Denmark
Galis and Gyberg [121]	ANT	-	Interview	-	3 landlords, 7 tenants	Residential	Linköping, Sweden
Xu et al. [119]	SNT	Type of affiliation network	Simulation, Artificial Neural Network	-	-	Residential	Albany - New York, United States
Chiu et al. [110]	SPT; ANT	Interactive adaptation (no specific construct was reported)	Interview, images from corresponding buildings	Narrative analysis of interviews	10 households	Residential	London, United Kingdom
Hansen [109]	SPT	Socio-cultural factors, household demographics, building factors	Survey	Regression/path analysis	1,198,442 households	Residential	Denmark
Lazowski et al. [115]	Energy Cultures Framework	Norms, material culture, practices	Interview	Narrative analysis of interviews	15	Residential	Toronto, Canada
Hess et al. [108]	SPT	Practices, meaning (norms, values, wants), Competence (factual knowledge, self-efficacy), material elements	Survey	Ordinary least squares regression	5015 participants	Residential	Switzerland
Yin and Shi [123]	SNT; TPB	Social network embeddedness, low-carbon behavioral intentions, low-carbon household behaviors	Survey	Structural equation modeling	355 participants (families of university students)	Residential	China
Debnath et al. [107]	SPT	Household practices, appliance characteristics, built environment	Survey	Structural equation modeling	1224 households	Residential	Mumbai, India
Jurisoo et al. [114]	Energy Cultures Framework	Norms, material culture, practices	Interview	Narrative analysis of interviews	32	Residential	Lusaka, Zambia
Economic							
Asensio & Delmas [130]	Framing Theory, Behavioral Economics	Framing (cost vs. health)	-	Regression (econometric modeling)	118	Residential	United States
Lundgren & Schultzberg [132]	Self-Control Theory	Beliefs regarding price-sensitivity; Attitudes regarding the price of electricity; Monitoring and upgrading activities	Survey, other	Dynamic structural equation modeling	102 residents (experimental survey)	Residential	Sweden (experimental survey) & Netherlands (survey development)

STS – Socio-technical System; **SPT** – Social Practice Theory; **ANT** – Actor Network Theory; **SNT** – Social Network Theory; **TPB** – Theory of Planned Behavior.

4.6.2. Sociological theories

4.6.2.1. Theoretical approaches and general findings. In recent years, sociological approaches to study the built environment have become more prominent. From this point of view, the applied theories within the literature include the Energy Cultures Framework, Social Practice Theory, Socio-technological Systems Theory, Actor-Network theory, and the Social Network Theory. Table 8 provides an overview of these studies.

The application of sociological approaches such as Social Practice Theory demonstrates the complex interplay between technologies and the ways in which individuals understand and use them as well as their influence on energy consumption [105]. In addition, perspectives from Energy Cultures have helped illustrate what factors shape occupants' outcomes (e.g., individual's choices) in terms of energy conservation behaviors. One example is the incorporation of lifestyle and infrastructure in the analysis of energy use [107,111,114,115,121]. Research has shown how material cultures shape cognitive norms, people's choice of technologies, and the resulting impact on energy practices [107,111]. These everyday social interactions determine household behaviors, such as cooking practices [114], reinforced by certain external factors [111, 115]. As an example, Hansen [109] shows that even when controlling for building characteristics and composition of household occupants, socio-cultural factors significantly influence heating practices in residential buildings. Further, the interactions between different actors and social networks embedded within and between households can significantly improve residents' low-carbon household behaviors and energy efficiency performance at the inter-building level [119,121,123].

Similar to psychological studies, sociological approaches also highlight the importance of demographic variables on behavior in buildings. These factors include gender and age [121,123], education, and immigration status [109]. Contextual factors such as family scales, monthly incomes and consumption, housing size, living area [123], and rehabilitation housing [107] are also important factors in shaping energy use.

Finally, sociological approaches showcase the vital role habits and broader behavioral routines play in explaining the divergence of consumption patterns observed between households living in similar conditions [117]. It has been shown that various factors (i.e., existing cultures, self-interest, short-sightedness, etc.) inhibit the ability to change ingrained habits over time [115]. Work by Gram-Hansen [105] provides evidence that rational thought processes alone are not enough to explain how people do or do not change standby consumption habits. Chiu et al. [110] further comment on the challenges of tying behavior in buildings to conscious decisions by occupants, suggesting that heating and cooling practices stem in part from the complex and intertwined nature of practices, material arrangements, and infrastructures.

4.6.2.2. Methodological approaches. Nearly all the studies examining mixed systems were conducted in residential environments across a relatively diverse geographic scope. Locations included research from the United States and Canada, China, Europe, New Zealand, Africa and India. Almost all studies were field studies, except for one simulation approach [119]. As shown in Table 8, nearly half implemented quantitative survey methods, while the other half performed qualitative interviews, and one study used observational analysis. The dependent variable analyzed in each of the identified manuscripts varied widely and included topics such as general energy consumption and conservation, household energy practices, such as cooking, washing and drying clothes, cleaning, water, and space heating-related behaviors, standby electricity consumption, and showering. The sample sizes of these studies varied significantly as well, ranging from as few as 10 individuals to over a million data points.

4.6.3. Economic theories

Only two papers within the mixed systems category used economic theories to understand human behavior in the built environment, each using a different theoretical framework.

4.6.3.1. Theoretical approaches and general findings. The work of Asensio and Delmas [130] primarily draws on Framing Theory while Lundgren and Schultzberg [132] use Self Control Theory to frame their research. Table 8 provides an overview of these two studies. The findings of these studies address different issues with regard to understanding the factors that drive behavior in buildings. The work in Refs. [130] showcases the importance of framing information, as the result indicate that framing information about energy use in terms of health consequences as opposed to cost produces more persistent reductions in energy use. Alternatively, research in Ref. [132] finds inconsistencies between beliefs of individuals regarding energy efficiency and their actual actions, suggesting people who believe they are energy efficient often use as much energy as other households.

4.6.3.2. Methodological approaches. Both studies had sample sizes of just over 100 and analyzed the results of two real-world interventions aimed at reducing energy use through feedback in the residential sector. While they primarily focused on energy savings broadly, each study also aimed to examine behavior across a wide array of building systems, including plug loads, lighting, space heating and cooling [130], turning off appliances [132] and monitoring energy use (both studies). The studies relied on statistical modeling methods to analyze the results and represent information from the United States and Sweden.

4.6.4. Discussion and identified gaps

Taken as a whole, the vast majority of papers within the mixed systems category applied psychological theories or factors to understand behavior in buildings, followed by sociological and economic approaches, respectively. As discussed in the previous sections, the most commonly used theories across the sample were the Theory of Planned Behavior (psychology) and Social Practice Theory (sociology). Outside of these two theories, many theories across all three disciplines are only applied once, making it difficult to robustly compare the insights derived from the application of each theory.

Interestingly, studies seeking to understand behavior in residential buildings appear across all three disciplines reviewed, whereas non-residential buildings have been primarily assessed in terms of psychological theories. This points to the opportunity to apply sociological and economic theories to enhance understanding of human interaction with commercial building systems. In addition, we find that survey-based studies are the most common approach to applying theories to understand mixed systems. This is particularly true with regard to theories from psychology, whereas interview approaches are most commonly used to test sociological theories based on the papers in this sample. This potentially shows disciplinary bias with regards to both methodology and building types assessed. As many of the studies find, demographic variables and contextual factors emerge as important factors in shaping energy use; however, this finding stems from studies conducted primarily in Western Europe, the United States, and China. As a result, a need exists for research across wider geographical spectrum, in particular within developing countries, to better understand how different cultural and demographic factors may impact behaviors across building systems.

Finally, as mentioned above, there is no common agreement on the influence of the mentioned theories on mixed systems – probably due to differences in location, target sample, study aims, and the number of analyzed buildings considered, among other factors. For instance, results showed mixed effects of certain theories' constructs on energy-savings and energy conservation intentions. Similarly, mixed results exist with regards to predictors of energy use, whether it can be better explained by socio-demographic variables or socio-psychological constructs [164]. As many of the studies measured general energy conservation behaviors and intentions by means of self-reported measures, further research should focus on the collection of real data – and inclusion of a control group – from energy use in buildings for validation purposes.

5. Discussion and directions for future research

In this literature review, we aimed to identify the studies that have applied different behavioral theories to explain occupant interactions with different building systems. In section 4, we provided a detailed overview of these studies including the applied behavioral theories and methodologies, their general findings, and some of the existing gaps within the literature specific to each building system. In this section, we discuss a number of general shortcomings and gaps that were commonly identified across all or multiple sections and provide a number of considerations for future research in this area.

5.1. Improved design of studies and data collection

A number of shortcomings identified within the reviewed papers related to the design and execution of the studies. Specifically, limited empirical and naturalistic studies exist that attempt to explain occupant interactions with specific building systems through behavioral theories. Rather than through empirical studies, many of the reviewed studies were conducted through surveys and questionnaires, likely due to the lower amount of resources, both time and money, needed. These questionnaires asked participants a few single item questions in order to examine the proposed psychological theories. Research could gain further insight, as well as confidence, about the findings of survey-based studies if they were integrated with additional measures, such as building data collected from smart meters or monitoring systems. At times, surveys may not be sufficient to generalize of how particular behavioral theories apply in these contexts. There is a need for a greater number of studies to collect data in naturalistic settings in addition to the self-reported survey studies.

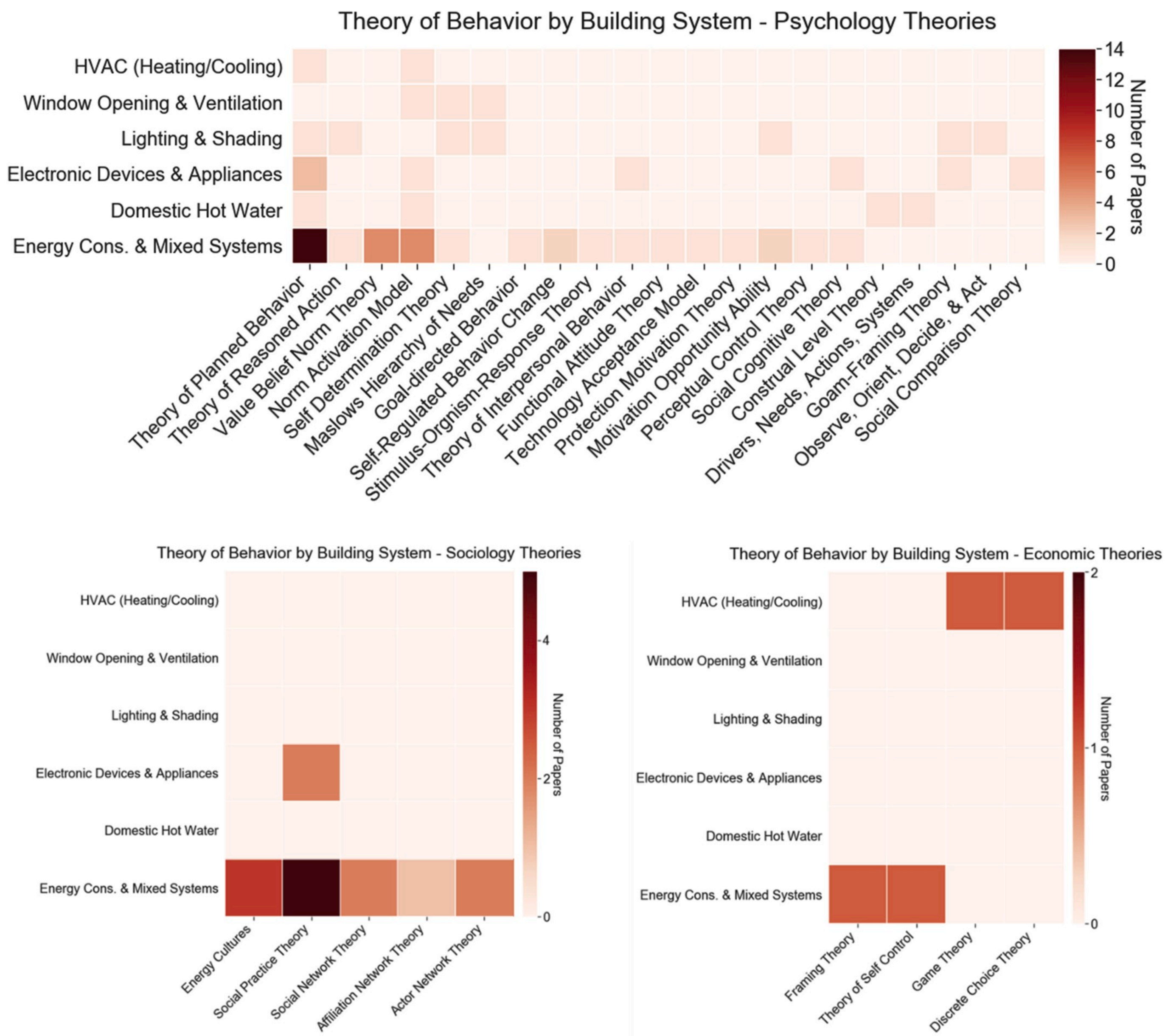

Fig. 2. The applied behavioral theories broken down by building systems. In this figure the top image provides an overview of the psychological theories, bottom left is the sociological theories, and bottom right is the economic theories identified within the reviewed papers.

Additionally, studies are conducted over a short period of time with small sample sizes. Researchers conducting future studies in this domain should use methodologies such as power analyses to identify the required sample size in order to confidently be able to detect the proposed effect. Currently, there is still a trade-off between sample size (mostly self-reported savings) and monitoring opportunities (i.e., to validate questionnaire results with actual, measured consumption). Fortunately, we see a trend towards more ubiquitous smart metering; as a result, monitoring as a means of validation will be possible on a larger scale in the near future.

5.2. Deeper dive into behavioral theories

As shown in Fig. 2, the majority of the identified studies applied very few and well-known theories; for instance, within psychological theories, the Theory of Planned Behavior is the most commonly applied theory across all building systems, followed by the Norm Activation Model and the Value Belief Norm theories. Although these theories are most commonly applied and studied, they may not be the most appropriate theory to explain occupant interactions with a specific or combination of systems. For instance, in recent years, the Theory of Planned Behavior and similar models have often been criticized by social scientists for simplifying behavior too much and some argue they are applied frequently because they are linear in nature and, therefore, more compatible and easily transferable to engineering models [165,166]. As a result, in future studies, researchers should move beyond these commonly studied theories to explore the extent to which less-commonly applied theories could further explain the role of occupant interactions with different building systems.

As shown in Section 4.6, the majority of the identified papers focused on applying behavioral theories to multiple systems (mixed systems). Although mixed systems studies may be more realistic due to incorporating many behaviors and the connections between them, disentangling the results can be quite difficult. Future studies should incorporate a cleaner design of studies that allow for disentangling of the results. Additionally, some of the identified studies focused on applying only specific constructs within a theory, instead of considering all elements collectively. In the design of studies, researchers should ensure all constructs are explicitly considered and accounted for.

As explained above, the majority of the reviewed studies examined how very broad, overarching behavioral theories apply to occupant behavior in buildings. However, a deeper dive into how more nuanced behavioral theories drive occupant behavior and interactions with different building systems is needed. For example, while prior research has found that goals are motivating than a lack of goals, a large stream of research has also found how some goals are more motivating than others (e.g., specific goals vs. nonspecific goals [167]), or how goals can sometimes backfire (e.g., Ref. [168]). Therefore, by diving deeper into more specific behavioral theories, experimental studies can better evaluate occupant responses and interactions with different building systems, and provide a more comprehensive framework on how building systems should respond to the dynamic changes in occupant behavior. Further, while it is beneficial for researchers to help occupants reach particular goals (e.g., reduce energy consumption, increase recycling rates, open shades, or turn the light off), they should also be cautious of setting too many goals for the occupants within their designed experiments. Indeed, prior research has found that when people make plans for too many goals, they often fail to reach them [169]. To properly identify and apply these specific behavioral theories, there is a greater need for close collaborations between the technical and social disciplines, as the researchers in the technical discipline can benefit from identifying more nuanced behavioral theories and proper design of experiments, while social scientists can benefit from learning how building systems operate and how different environmental factors may impact building-system operations.

Researchers should remember that human behavior is complex and challenging to predict. Often, the behavior is multiply determined. On the one hand, it is necessary and worthwhile to examine whether a specific theory can explain occupant interaction with different building systems. However, researchers should be careful to not over-claim that only the specific theory that they are examining can explain the observed behavior.

5.3. Interdisciplinary approaches to determine drivers of behaviors holistically

Future studies should integrate measures from various fields, such as physiological data, productivity-related information, and health and well-being metrics, in order to gain a more complete understanding of occupant behaviors and interactions. However, to achieve this, researchers should strongly consider forming interdisciplinary teams, consisting of researchers with expertise in different domains such as social sciences, human factors, and medicine (along with the technical domains).

With the emergence of new biometrics and human sensing technologies over the past decade, there has been a significant increase in research studies using physiological measurements to better understand and predict changes in occupant comfort levels. As a result, there are a number of recent synthesis studies evaluating how occupants' biological and physiological states change in response to different environmental conditions. Integrating behavioral theories with these physiological measurements can provide a more holistic framework of occupant comfort and behaviors within buildings. Furthermore, as the number of studies in this area increases due to automated and advanced sensing technologies, researchers should also conduct studies on identifying different approaches to conserve occupant security and privacy. Recently introduced system architectures, such as edge or fog computing, may help address some of the end-user privacy concerns. However, more research is needed in this area to further explore how these architectures can be implemented within buildings.

5.4. Increase the number of studies in different geographical locations

A major observation within this literature review identified that these studies are being conducted in a select few countries and geographical locations. As shown in Fig. 3, the majority of the studies were conducted in the United States, Western Europe, and China. No identified study was conducted in South American, only one study was conducted in an African country, and very few studies were conducted in the Middle East or eastern Asia (excluding China). Within the United States and China, most of the studies were concentrated in specific geographical locations. For instance, in the US, the majority of the studies were conducted in the west or northeast regions; similarly, in China, the majority of the studies were conducted on the eastern side of the country. In general, more studies should be conducted throughout different regions of the world as different geographical, climatic, cultural, and societal factors may influence how occupants behave and interact with different building systems. Furthermore, with the changing global climate and more frequent extreme weather conditions, more studies should be conducted in extreme environments (e.g., Alaska) to identify certain factors that need to be considered in designing and operating future buildings as well as enhancing the adaptability of building systems to both environmental and occupant related changes.

In designing studies that intend to collect data from different geographical locations or across multiple countries, researchers should also consider cultural and language differences within the design of their studies. For instance, translation issues arise when conducting surveys internationally [170,171]. Researchers should conduct pre-test studies within specific regions of interest, in which participants (members of the target sample) can provide feedback on the survey instrument and procedures, to ensure the meaning of questions are conveyed properly and cultural/societal factors are fully considered.

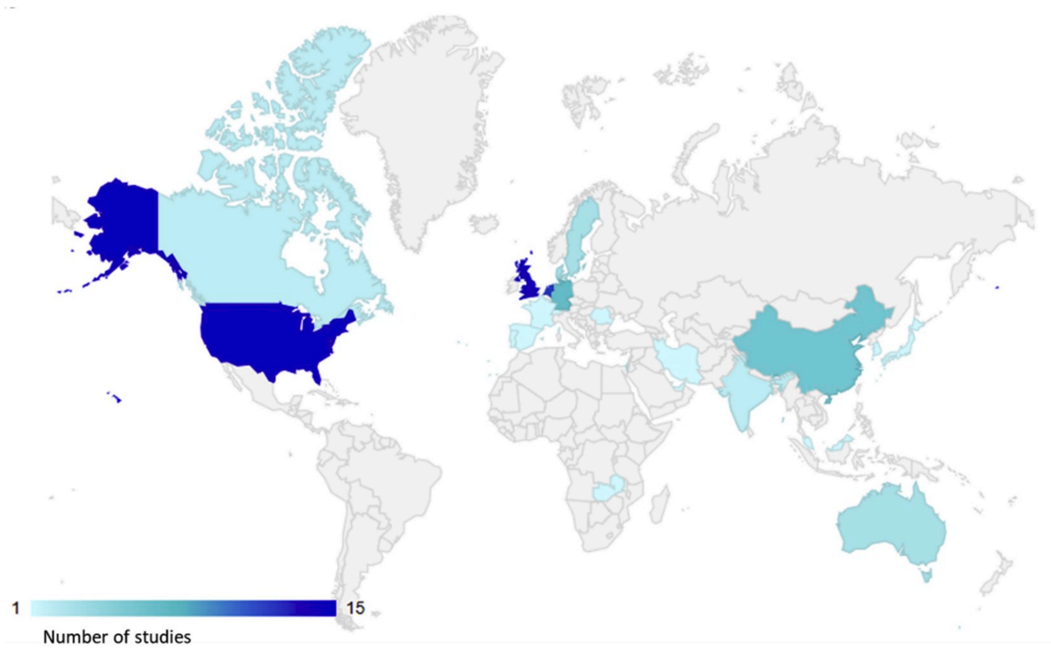

Fig. 3. Different countries and geographical locations where researchers applied behavioral theories to explain occupant interactions with different building systems.

6. Conclusion

In summary, we have reviewed and categorized the behavioral theories applied to explain occupant behavior and interactions with major building systems. By providing an overview of the diverse theories our review identified (Section 3) and how they have been applied through literature to explain occupant interactions with different building systems (Section 4), we have identified the current state and challenges associated with understanding the driving factors in occupant behaviors and interactions in residential and non-residential buildings from an applied theoretical perspective.

The majority of existing research in this area focuses on very few, well-known behavioral theories such as the Theory of Planned Behavior (TPB), Value Belief Norm, Norm Activation Model, and Social Practice Theory. Compared to psychological theories, there are significantly fewer studies investigating how sociological and economic theories can explain occupants' behavior and interactions with different building systems. Among sociological theories, the theory of Social Practice theory and Energy Cultures were more commonly studied theories and very few economic theories seem to exist in literature.

Moving forward, future research studies should continue to draw upon behavioral theories across the disciplines to investigate how they individually and collectively explain occupants' interactions with building systems. Additionally, the recent increase in availability of data from building systems and occupant-centric information (i.e., thermal and lighting comfort, physiological sensing, emotional sensing, personality traits, etc.) provides engineers and social scientists rich new opportunities to collaborate together in studying short-term and long-term behavioral changes in indoor environments. As work in this field continues to advance, we encourage researchers to explore and compare more diverse geographic locations to cultivate a deeper understanding of the cultural similarities and differences in occupant-building interactions. Researchers conducting such studies are highly recommended to share their datasets with the research community to motivate other researchers investigate different dimensions of occupant behaviors. Lastly, we hope this literature review paper can motivate more researchers to conduct more nuanced and interdisciplinary studies based on a sound theoretical foundation to better understand the role of occupant behavior in the operation of different building systems.

Declaration of competing interest

We wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

Acknowledgment

The authors would like to thank the organizing committee of IEA EBC Annex 79 as the presented paper was shaped and conducted within a framework identified in IEA EBC Annex 79 and the authors have benefited from collaboration with researchers from this group. Additionally, Dr. Heydarian would like to acknowledge funding received from the National Science Foundation under Grant no. 1823325. Dr. Schweiker and Romina Rissetto would like to acknowledge funding received from the Federal Ministry for Economic Affairs and Energy (BMWi) under Grant numbers 03EN1002A and 03ET1563A, respectively. Dr. Anna Laura Pisello and Cristina Piselli would like to also thank the Italian Ministry of research for supporting the NEXT.COM PRIN 2017 project, 20172FSCH4_002 "Towards the NEXT generation of multiphysics and multidomain environmental COMfort models: theory elaboration and validation experiment." Additionally, Claire McIlvennie would like to acknowledge funding support from the National Science Foundation IGERT Smart Grid program and Gund Institute for Environment at the University of Vermont, and Lawrence Berkeley National Laboratory. Any opinions, findings, and conclusions or recommendations expressed in this manuscript are those of the authors and do not necessarily reflect the views of the listed funding agencies.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.buildenv.2020.106928.

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