Title
How people use thermostats in homes: A review

Journal
Building and Environment, 46(12)

ISSN
03601323

Authors
Peffer, Therese
Pritoni, Marco
Meier, Alan
et al.

Publication Date
2011-12-01

DOI
10.1016/j.buildenv.2011.06.002

Peer reviewed

Building and Environment 46 (2011) 2529–2541

Contents lists available at ScienceDirect

Building and Environment

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

How people use thermostats in homes: A review

Therese Peffer [a,*], Marco Pritoni [b], Alan Meier [c], Cecilia Aragon [d], Daniel Perry [d]

[a] California Institute for Energy and Environment, 2087 Addison Street, 2nd Floor, Berkeley, CA 94708, USA
[b] Mechanical & Aeronautical Engineering, UC Davis, Davis, CA 95616, USA
[c] Lawrence Berkeley National Laboratory, 1 Cyclotron Road, Berkeley, CA 94720, USA
[d] Department of Human Centered Design & Engineering, University of Washington, 407A Sieg Hall, Box 352315, Seattle, WA 98195, USA

ARTICLE INFO

Article history:
Received 1 March 2011
Received in revised form
31 May 2011
Accepted 3 June 2011

Keywords:
Residential
Thermostat
Usability
Energy consumption
Control
User interface

ABSTRACT

Residential thermostats control a substantial portion of both fuel and electrical energy—9% of the total energy consumption in the U.S. Consumers install programmable thermostats to save energy, yet numerous recent studies found that homes with programmable thermostats can use more energy than those controlled manually depending on how—or if—they are used. At the same time, thermostats are undergoing a dramatic increase in capability and features, including control of ventilation, responding to electricity price signals, and interacting with a home area network. These issues warrant a review of the current state of thermostats, evaluating their effectiveness in providing thermal comfort and energy savings, and identifying areas for further improvement or research.

This review covers the evolution in technologies of residential thermostats; we found few standards and many features. We discuss studies of how people currently use thermostats, finding that nearly half do not use the programming features. The review covers the complications associated with using a thermostat. Finally, we suggest research needed to design—and especially test with users—thermostats that can provide more comfortable and economical indoor environments.

1. Introduction

Heating and cooling homes consumes a substantial portion of energy. Most households in the U.S.[1] use thermostats to control the heating and/or cooling system in their home; in 2005, approximately 97% of households in the U.S. had a heating system and over 75% had air conditioning (Table 2.6 in [1]). In 2008, about a quarter (28% or 6.04 quadrillion BTUs) of the total residential source energy consumed was for heating and 14% (3.07 quadrillion BTUs) for cooling [2]. Most (65%) of the energy supplied by fuels (primarily natural gas, also fuel oil and propane) was for heating [3], but the use of electricity for heating nearly doubled from 1985 to 2005. While approximately 20% of total residential electrical energy was used for cooling, air conditioning constitutes the largest single contributor to peak electricity demand (which can lead to brownouts and wildly variable wholesale prices) [4]. Moreover, electricity use for air conditioning is rapidly increasing, due to population growth in hot climates and greater demand for comfort. In 2009, nearly 90% of newly constructed single family homes included air conditioning [5]. In 2008, energy for heating and cooling homes comprised approximately 42% of the total source residential energy and about 9% of the total source energy in the U.S. [2,6].

The basic function of the typical residential thermostat—to set a target temperature, see the current temperature, and control the equipment accordingly—has remained constant over the past sixty years. A second—and expanding—role is to save energy. Many new features and functions have emerged in the past twenty years to facilitate the energy-saving role. While the thermostats' capabilities to control temperature are well understood, less is known about the effectiveness of the technologies devised to enable savings. The uncertainty in these savings is increasingly important because manufacturers are adding many new features and functions that affect the ability and ease of saving energy. The most advanced thermostats control multiple zones and humidity levels. Still other features include one-touch energy-savings, access to weather, display of energy consumption, alerts for maintenance (e.g., battery, filter), and diagnostics [7]. Remote control is becoming a popular feature as smart phones and Internet access become ubiquitous. Some changes are dictated by regulations or utilities. Since 1978, California building codes have required thermostats with night setback capabilities and many other regions followed. The Environmental Protection Agency (EPA) established

* Corresponding author. Tel.: +1 510 289 4278.
E-mail address: therese.peffer@uc-ciee.org (T. Peffer).

[1] The thermostats described in this paper mostly control forced-air systems found in North Amercian homes. However, many of the same issues apply to other heating and cooling systems found in Europe, Australia, and East Asia.

0360-1323/$ – see front matter
doi:10.1016/j.buildenv.2011.06.002

technical specifications for programmable thermostats for its EnergyStar program in 1995. A relatively recent development is residential demand response: utilities with high costs of supplying peak power want to communicate directly with thermostats because adjusting temperatures in cooperating customers' homes is cheaper than building new generation capacity.

This review describes the history and current state of the art of thermostats in Sections 2 and 3. Section 4 draws from the literature to understand what types of thermostats are installed and how they are used across the U.S. Section 5 discusses the energy savings from thermostats. Section 6 categorizes the types of problems in adopting programmable thermostats. Section 7 pairs what we know with what we don't know in suggesting areas for future research and policy implications. Section 8 of the review is the conclusion.

2. History

Since the first fire was lit in a cave, heating and cooling for thermal comfort in dwellings has required human intervention [8]. The Romans were among the first to move from the concept of a simple open fire to a central heating system, where hot air from a wood fire flowed through under-floor chambers or hypocaust [9]. In fact, the word thermostat is derived from the Greek words *thermos* ("hot") and *statos* ("a standing"). Cornelius van Drebbel (born 1572 in Alkmaar, Holland) is commonly credited with inventing the thermostat—automated temperature control in the form of a mechanical device; Van Drebbel was able to regulate the temperature of ovens and chicken incubators [8,10].

Modern thermostat history in the U.S. revolves around two companies who are still in the business of building thermal controls today: Johnson Controls and Honeywell. In 1883, Warren S. Johnson received a patent for the first electric room thermostat; upon his death in 1911, his company Johnson Controls focused on temperature controls for nonresidential buildings only [11]. In 1885, Albert Butz developed a furnace regulator that used a "damper flapper" to control air entry (and thus heat output) to a furnace. His company, the Electric Heat Regulator Co., eventually became Honeywell Inc [12]. In 1906, Honeywell produced the first automatic programmable setback thermostat, using a clock to turn the temperature down at night and up in the morning. The first thermostat with an anticipator—a means of reducing temperature overshoot—was produced in 1924. The first modern thermostat controlling a central heating system (typically a forced air system in the U.S.) used a bi-metallic strip to measure temperature change and used mercury in a tilting glass tube to provide contact with the electrodes in the tube to control the furnace. The typical thermostat interface was a simple rectangular box on the wall that used sliding levers to control the temperature; the ubiquitous Honeywell Round, which emerged in 1953 and is still available today, required the user to turn the round dial. These types of thermostats are often termed manual, standard, or mechanical thermostats. Both current temperature and the target or desired temperature were displayed on an analog scale showing temperature range.

Over the past 40 years, different policies have driven the development of features in thermostats. The first oil crisis in 1973 spawned the creation of the first energy code (Building Energy Efficiency Standards) in California in 1978, part of which required clock or setback thermostats for new homes. These thermostats were designed to save energy by automatically relaxing temperature setpoints when people are sleeping. Studies performed in the 1970s, based on models of energy flows through a house, suggested that on average a daily 8-h nighttime setback could bring approximately 1% reduction in natural gas consumption for each degree Fahrenheit offset [13]. This result became and remains the rule of thumb that guides much of the discussion on the effectiveness of programmable thermostats with gas- and oil-fired heating systems.

The physical human interface on thermostats has evolved partly because of technical innovations and partly pushed by regulations. The Americans with Disabilities Act (ADA) standards introduced in 1988 mandated controls that did not require the twisting of one's wrist [14]. This requirement along with the trend away from mechanical thermostats with their moving parts towards semiconductor electronic manufacturing drove the "modern" look for thermostats. By the early 1990s, the new thermostat was a plastic rectangular box with few moving parts; thermistors replaced bimetallic strips, digital display replaced analog, and push buttons replaced dials and slider bars. The addition of memory allowed the storage of data, such as target temperatures for different times of day, and required a power source.

In 1995, the Environmental Protection Agency's EnergyStar program included programmable thermostats, suggesting that homeowners could save about $180 a year with a programmable thermostat [15]. EnergyStar requirements included certain features: default energy-saving and comfort setpoint temperatures, cycle rate setting, recovery systems, and a hold or override option. Consumers understood that the EnergyStar emblem on an appliance indicated energy efficient equipment; manufacturers had to comply with EnergyStar eligibility requirements.

Throughout the 1990s programming grew more complex, with these features plus programming schedules for weekend/weekday $(5 + 2)$, seven-day, or vacation. More recently, part of the 2008 California Building Energy Efficiency Standards, commonly referred to as Title 24, requires that programmable thermostats have the ability to set temperature preferences for at least four different time periods per day.

Utilities across the globe are exploring time-varying price tariffs to reduce peak electricity demand—driven primarily from space heating (e.g., in hydroelectric-rich New Zealand and Canada) and cooling systems (e.g., in the U.S.). This created the demand for programmable communicating thermostats that can receive price or reliability signals from the utility. In California, while these thermostats were not included in the 2008 energy code, this is expected for future iterations; at the federal level, this will most likely start with the new EnergyStar specifications regarding climate controls (a subset of programmable thermostats) that include communication and time of use price level indication [16].

Remotely controlled thermostats have become both feasible and possible with the growing prevalence of cell phones, home area networks (HAN), and the Internet in residences. Several applications have been developed to enable control of a thermostat using a mobile phone. Global Positioning Systems (GPS) in mobile phones can be used to convey occupancy and proximity information to thermostats, which can then predict arrival times of a home's occupants and modify the setpoint accordingly [17].

Many aspects of a programmable thermostat's functionality have been transferred to the Internet. An Internet thermostat describes a programmable thermostat that connects to an IP (Internet Protocol) network; models are currently being made by Proliphix, Aprilaire, and Ecobee. Internet connectivity has spawned companies such as EcoFactor, which sells an energy-saving thermostat service. One network-enabled thermostat has a removable standardized communication module (based on U-SNAP (Utility Smart Network Access Port)) to connect the thermostat to a Home Area Network via various wireless standards, such as ZigBee, Z-Wave, RDS (Radio Data System), WiFi, FlexNet and Trilliant [18]. Further, companies such as Control4 who specialize in home automation have added a comfort function to their home management interface to remotely control an Internet thermostat from the TV or other display. Likewise, security companies such as ADT have also included thermostats in their networks.

Thermostats have come a long way from simply controlling a heating or cooling unit and displaying current and target indoor temperatures (Fig. 1). Today's thermostats can control ventilation, whole house fans, humidity, and multiple zones. The user interface can be remote (e.g., controlled through web or smart phone), voice-controlled, a large full color LCD or touchscreen. Displays now can include outdoor temperature, messages from the utility, or maintenance alerts (e.g., battery or filter replacement warning).

These trends have shifted the thermostat from being a simple wired appendage of the heating and cooling systems to a separate product resembling software or consumer electronics. This is also reflected in the shift in the orientation of companies involved in thermostats, from more mechanical (e.g., manufacturers of HVAC equipment) to those more familiar with consumer electronics and communications.

3. Architecture & features

A basic thermostat has four components: a temperature sensor in the desired environment, a switch or actuator to the physical target of heating, ventilating, and air conditioning (HVAC) equipment, a feedback loop between the two, and some means of displaying the current (and target) temperatures as well as providing a means for the user to change the target temperature. Electronic devices with digital displays have largely replaced mechanical and mercury-based thermostats; wired connections are slowly being replaced by wireless. Advances in communication networks have allowed thermostats to become increasingly disaggregated into separate components. Fig. 2 shows a schematic of thermostat components, which may or may not be packaged together. The temperature sensor may be wireless, communicating with the controller via radio frequency; the user interface may be a mobile phone or web page.

1. *Sensors*: basic functioning of a thermostat requires at minimum a single room temperature sensor. Additional sensors could monitor humidity, outside temperature or additional inside temperature points, occupancy through infrared sensors, or connected to a security system that includes door entry or window sensors.
2. *Actuators*: the thermostat uses a switch or relay, whether mechanical or electronic, to turn on or off the target equipment, whether furnace, fans, or compressor for the air conditioning system. Other potential equipment includes an economizer, whole house fans, and a humidifier/dehumidifier.
3. *Control logic*: for simple thermostats, the control logic is simply a feedback loop that compares the target temperature with the current measured temperature to determine when to turn on or off the equipment. Mechanical thermostats handled this, plus anticipation (to prevent overshooting the target) and hysteresis (a deadband of temperature typically ±1 °F around the target temperature to prevent frequent switching of the equipment). Modern programmable thermostats provide anticipation, hysteresis, as well as other features through electronics. Data is read from the settings, user interface, and sensors, and a set of algorithms determines when the system switches on and off.
4. *User interface*: the user interface (UI) represents a means for the user to provide input for thermostat control and view a display of information. The UI allows users to change the target temperature setting—and on programmable thermostats, input a schedule of changing temperature settings—while displaying information, such as current and target temperatures. The thermostat interface can be mechanical with slide bars, digital with push buttons, or digital with touchscreen. New interfaces include web interfaces, mobile interfaces, TV interfaces, audio, and remote controls.
5. *Communication interface*: at a minimum, a thermostat must communicate with the HVAC system, generally through wired connections. Additional capabilities require communication using various protocols; examples include connection with a home area network, receiving price or reliability signals, streaming local weather forecast, receiving control signals through an external optimization service, or communication with interval meters.
6. *Memory*: programmable thermostats require memory for data storage; memory can be permanent or volatile (i.e., disappears when power is disconnected). These data, such as time of the day and target temperature for each program, are needed for the thermostat control logic.
7. *Power supply*: modern programmable and digital thermostats require electric power for operation. Batteries or low voltage ac power from the heating or cooling equipment typically provide this power; electric heating systems commonly use line voltage

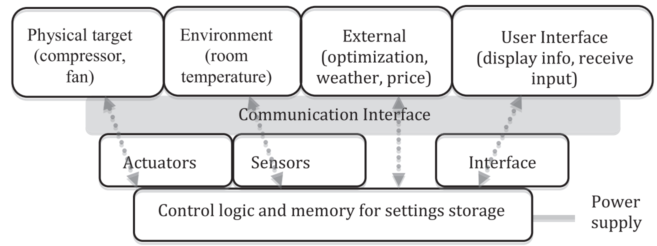

Fig. 2. Disaggregated components of a typical thermostat.

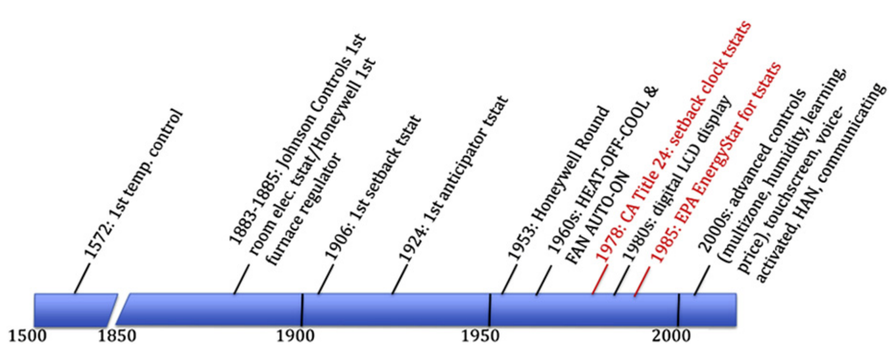

Fig. 1. Timeline of the history of residential thermostats.

power. Thermostats often employ both systems, using the batteries to preserve settings in the event of power outages or other failures.

3.1. Control features

Today's thermostats have a variety of features, both for control and the user interface, with different levels of sophistication. One range of features is related to *what* is under control. Thermostats typically control heating and cooling equipment, which can include forced air, radiant floor (typically using water) or radiant ceiling systems (water or electric), or radiators (typically steam). Some equipment, such as heat pumps, requires specialized control. Thermostats may also control related equipment, such as humidifiers/dehumidifiers, auxiliary heating systems, economizers, whole house fans, or other ventilation systems. High efficiency equipment often includes two stage systems with variable speed fans, which are controlled based on the difference in current and target temperature.

Another set of features of thermostats involves *where* the control lies. For example, a fan-delay relay at the equipment allows the blower fan to continue to run a few minutes after the compressor has turned off to take advantage of residual cooling. Some thermostats provide this control at the thermostat and allow adjustment of this time period. The anticipator, which turns off equipment before the setpoint is reached to prevent overshoot, may be adjustable (especially for heating) or not (cooling). Compressor protection, which requires the compressor to remain off for a few minutes minimum to protect equipment, is a typical feature often embedded at the HVAC controls.

A key issue is *how* these features work; some features with the same name (such as hold or recovery) have very different functions with different manufacturers. Some de facto standards have evolved, such as switches for heating/cooling mode (HEAT-COOL-OFF), auto switchover (automatically switch between use of heating and cooling equipment), and separate control of the blower fan (Fan-AUTO). For programmable thermostats, two push buttons to increase or decrease target temperature (as well as other functions) is fairly standard.

Some features have been driven by the EnergyStar program, such as default energy-saving and comfort setpoint temperatures and schedule, cycle rate setting, pre-comfort recovery, and hold and/or override options. Other policies, such as demand response dynamic pricing (described in [19]), are driving features such as communication and temperature setpoints that automatically respond to price. Other feature development is driven by increasing sophistication, such as multi-zone control, air filtering, and multi-stage HVAC equipment. While some thermostats do not indicate current time of day, programmable thermostats typically do—either allowing an internal clock to be set by the user or providing a means of updating the time automatically.

3.2. User interface features

Another set of features relates to the user interface of the thermostat. These features are categorized by what is displayed and how it is displayed. Typical information to be displayed includes current and target temperatures (in Fahrenheit or Celsius), day of week, time (12 or 24 h), and current schedule control mode (e.g., morning, day, evening or night); some displays show outside temperature, relative humidity, and/or local weather forecast. System status is often displayed by the position of a switch, or text or icon. Status information includes:

- thermostat is off or in heating, cooling, or auto switchover mode,
- fan is off or in auto mode,
- heating or cooling system, fan, or backup heating system is currently running,
- hold/temporary/vacation mode is active (supercedes regular programmed schedule).

Another type of display is an alert, such as indication of a low battery or that the filter needs changing. Other types of information include help (e.g., tips, other information for easy set up, instruction manual), energy usage and or cost, messages from utility and/or current price tier.

The user interfaces of thermostats have evolved over time, both in how information is displayed and the means of user interaction. Early thermostats presented a needle-type marker that indicated current and target temperatures within a range of possible temperatures in an analog display (Fig. 3). The majority of programmable thermostats now use digital numbers to display temperature; some recent models have returned to numbers on an analog scale. Many programmable thermostats display text or numerical information on some sort of Liquid Crystal Display (LCD). The early models had relatively small monochrome screens that had space dedicated to specific information. In some models, a marker such as an arrow pointed to text (such as day of the week) printed on the plastic enclosure of the thermostat; the displayed marker changed position to indicate change in status or information. In recent years, the LCDs have grown larger, multi-colored, and screen space is shared—different information can be displayed in the same area at different times. Some thermostats use menus in a framework similar to personal computer interfaces to provide many layers of information structured on the same screen. Many programmable thermostats now have backlights for reading the LCD screen at night (Fig. 4).

Fig. 3. Older thermostat designs with slider bars, dials, and analog displays; Honeywell Round [20] on left and Honeywell Chronotherm setback thermostat on right (photo by T. Peffer).

Fig. 4. The evolution of the programmable thermostat from small LCD on LUX 1500 [21] on left to full touchscreen on White Rodgers [22] on right.

The user interaction has changed from sliding needle-markers and turning dials to push buttons and even touchscreens on some models. While early models used push buttons to control a single use—up, down, hold, next, reset, clear—some thermostats rely on context-sensitive buttons, that is multi-use buttons that control different features in different modes. Physical slider switches are still commonly used, although in touchscreen and web interface models, these are replaced with a virtual switch. Other conventions borrowed from computer interfaces include using OK, Back, and Save buttons.[2]

Many thermostats have controls or settings meant to be used rarely and/or only at installation. These functions are often hidden from apparent view, such as locating the switch for temperature display in Fahrenheit or Celsius on the back of the thermostat. A separate installer mode might include setting cycle rate or temperature differential (deadband); these features may be only accessible via a specific sequence of button pushes.

Manufacturers are constantly offering new interfaces. Voice control thermostats allow a thermostat to be set up and controlled by spoken commands. Some thermostats offer the user a selection of multiple languages. Others provide great flexibility, such as custom names for various programmed schedules. Audible touch confirmation is a feature that imparts an audio prompt to confirm entries. Single button pushes allow easy program switches, such as changing to Daylight Savings Time versus Standard Time or changing to an occupied or energy-savings mode.

4. Thermostat ownership & usage

4.1. Thermostat ownership

We found data on thermostat ownership mainly from surveys. The Residential Energy Consumption Survey (RECS) is a national area-probability sample survey (about 4000 homes every four years) that includes several questions about presence, type, and usage of thermostats. The American Home Comfort Study (AHCS) also surveys 30,000 homeowners every two years; the 2008 survey was conducted via the Internet. About 86% of U.S. homes have a thermostat of some type controlling heating and/or cooling systems [24,25]. Over time, the penetration of programmable thermostats has increased in response to codes, decreased costs, needs for additional features (e.g., central air conditioning), and the desire to save energy. Building codes and other efficiency programs have accelerated the transition to programmable units.

Currently, about a third of U.S. homes have programmable thermostats [24,25]. The exact saturation is difficult to determine because the estimates rely on consumer responses to surveys. Consumers do not universally understand the distinction between the types of thermostats even though manual and programmable thermostats have very different capabilities. While two major categories of thermostats—manual or programmable—are generally recognized, several surveys have indicated that lay people do not understand these terms. Manual thermostats—those that require human intervention and have no automatic features—are often called standard or mechanical. However, manual thermostats can have digital displays and operate with electronic sensors and switches instead of mechanical ones. The early setback or clock thermostats look like manual thermostats with their analog displays, but they are categorized as programmable thermostats, since they can automatically change temperature based on a timed schedule. In both the national RECS and California-based Residential Appliance Saturation Survey (RASS), the authors noted problems with people understanding the term programmable thermostat [1,26]. In RECS, the authors noted that when a clarifying phrase was added to the question regarding type of thermostat, the number of households reporting a programmable thermostat nearly dropped in half compared to the previous survey, from 44.9 million in 1997 to 25.1 million in 2001 [27]. RASS noted that the numbers listed were lower than expected, that is, the response rate regarding programmable thermostats in post-1995 houses was expected to be 100% due to the energy code, but was underreported.

Although programmable thermostats have been available for more than 30 years, only 30% of U.S. households have installed them. In the 2005 RECS, 14% of U.S. households reported having no thermostat, 30% (34.6% of thermostat owners) had a programmable thermostat, and 56% had a manual thermostat [1]. According to the AHCS, 36% of households had programmable thermostats in 2004, and the percentage increased to 42% in 2008 [28]. In California, the 2005 RECS reported 19% of households with no thermostat, 44% (54% of thermostat owners) with a programmable thermostat, and 37% with a manual thermostat [24]. The percentage of houses in California without thermostats differs from the national percentages due to milder weather, whereas the increased number of programmable thermostats in California versus nationwide is likely attributed to the last 30 years of energy code requiring a setback or programmable thermostat. Of those that used central air conditioning in California, 68% had programmable thermostats; this most likely reflects the fact that homes built in the past 30 years were more likely to have central air conditioning (Fig. 5). Another survey conducted in Seattle, the Residential Customer Characteristics Survey 2009, reported that programmable thermostats were installed in approximately 51% of households [29].

[2] We note that Honeywell holds a patent on the saving changes indication, which poses a constraint on other thermostat designs [23].

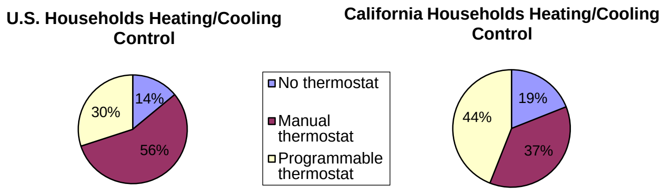

Fig. 5. Thermostat type in United States and California [1].

Thus, residential energy use (and savings) still depends largely on the settings of manual thermostats by the owners. This fraction will fall steadily in the next decade as older thermostats are upgraded through weatherization programs, utility incentives, and consumer initiatives to achieve energy savings and more features.

4.2. Thermostat usage patterns

Several studies show that programmable thermostats are set and programmed differently than manual thermostats. In a home with a programmable thermostat, the occupants can program a schedule to change the target temperature or setpoint. During the heating season, the temperature setpoint can be reduced ("set back") when the house is empty or at night; in the cooling season, the temperature setpoint can be increased ("set up") to prevent operation of the cooling system when not needed. In the 2005 heating season, about 60% of U.S. households with programmable thermostats reported using them to reduce temperature at night. Only 45% reduced the temperature during the day; the same survey indicated that approximately 51% of homes have someone home all day, which may explain why fewer household reduce temperature during the day than during the night [25]. During the cooling season, 55% of households with programmable thermostats set them to increase temperature at night as well as during the day [24]. According to the California 2003 Residential Appliance Saturation Survey (RASS), only 28% of households in California actively set up the temperature for air conditioning (AC) during the day, and the presence of programmable thermostats did not appear to dramatically affect setback behaviors [26]. Of the recent buyers of HVAC equipment, the American Home Comfort Study (AHCS) reported that 56% of homeowners always program their thermostats, 32% sometimes program, 9% never program their thermostats, and 3% do not know how [28].

In a study that compared the energy consumption of manual thermostats versus programmable thermostats in CA households, programmable thermostats were set slightly higher (i.e., 0.7–1.2 °F) than manual thermostats in the cooling season (which would save energy), but were not in OFF mode as often. In the heating season, programmable thermostats were set at higher temperatures than manual thermostats (which would cause more energy use), and far fewer were placed in OFF mode than manual thermostats [30]. A consumer survey conducted in Seattle revealed that a night setback was adopted by 86% of people with programmable thermostats and only by 60% of people with manual thermostats [29]. A study in California found that setpoints assumed in Title 24 energy code compliance software (similar to those required for EnergyStar eligibility) overestimated the cooling setpoint and underestimated the heating setpoints; in other words households in the study on average used a lower setpoint for cooling (used more energy) and a higher setpoint for heating (used less energy) than the default energy-saving setpoints [31].

Similarly, outside the U.S., setup and setback behaviors are not a common habit, as reported in several international studies. A cross-cultural study of energy behavior in Norway and Japan [32] reveals that less than 50% of Oslo's households setback temperature at night and 28% did not lower thermostat settings during weekends or vacations. Another northern European survey of 600 homes [33] showed that only 38% of the houses with thermostats lowered their temperature during the night.

Occupants regularly interrupt the programming of their programmable thermostat by selecting operating modes that suspend the programmed schedule: *hold* and *override* (sometime called temporary hold or temporary override) mode. *Override* allows the occupant to temporarily raise or lower the desired temperature typically until the next scheduled time program. The *hold* mode is a permanent change, and functionally transforms the programmable thermostat into a manual thermostat. A study conducted by thermostat manufacturer Carrier examined the operating mode of installed programmable thermostats in households within the jurisdiction of four utilities, LIPA, ConEd, SCE, SDG&E. Of the 35,471 thermostats monitored overall, only 47% were in program mode, in which the thermostat used the schedule previously input by the occupant to control temperature setpoints. The rest—53%—were in hold mode. The households within the two southern California utilities (SCE and SDG&E) showed a higher percentage (65%) in program mode, although it was unclear why [34]. In the AHCS, no distinction was made between override and hold. One question asked about the frequency of overrides for recent HVAC buyers (all the time 8%, often 12%, sometimes 36%, rarely 35%, never, 9%) [28]. It is difficult to know whether overriding "all the time" means the thermostat was in hold mode or not.

Several studies have examined temperature swings, comfort, and control within homes [31,35–39]. These indicated that thermal comfort preferences at home are very different from that in offices: there is a wider temperature range, because of greater control (i.e., occupants opened windows, and had greater freedom to change thermostat settings, clothing, and activity level) [40] and because of costs [41]. A recent national survey found that 49% of homeowners were very much satisfied with their home comfort systems, 43% somewhat satisfied, and 8% not at all satisfied [28]. There was a slight correlation between programmable thermostats and satisfaction: 45% of those very much satisfied had programmable thermostats compared to 32% of those who were not at all satisfied [28]. A preliminary study indicated that socioeconomic class may affect these responses: in a recent weatherization study by one of the authors (Meier) in low-income households, the top two complaints were mechanical ventilation and the programmable thermostat. However, thermal comfort throughout the home tends to be problematic—68% of homeowners found at least one room too hot in the summer and 60% found at least one room too cold in the winter [28]. When asked about seeking improvements to their home comfort system, 89% of homeowners listed greater energy efficiency as very important, but many listed issues with thermostat as very important as well: more even temperature (65%), better temperature control (68%), faster heating and cooling (64%) [28]. Other issues were listed as very important—such as better air purification (76%), improved air flow (69%), and better humidity control (64%) [28]. However, most commercially available thermostats (the main device to affect house thermal environment) control only air temperature, leaving all other parameters unmonitored and uncontrolled.

There are no set standards for thermal comfort in residences, although New York rental housing has a minimum indoor temperature requirement for the eight coldest months of the year [42]. A few have suggested the Adaptive Comfort Standard described in ASHRAE 55-2004 as an appropriate standard [40,43] since houses by law have operable windows for ventilation; this standard allows a wider comfort temperature range given the occupants' ability to adapt. Thermal comfort has been defined and studied both in the lab and field, primarily in the commercial sector

[44–49]. Many factors have been found to influence thermal comfort, such as air temperature, radiant temperature, air speed, humidity, level of clothing/activity [44,50,51] as well as psychological, behavioral, and physiological influences [52–56]. These may explain the difference in heating and cooling season temperature offsets [57]. In general, comfort temperatures have been increasing in winter and decreasing in summer over the past several decades [58,59]. Several studies indicated control as a major issue in thermal comfort at home [35,38,40,60]. However, most of the thermal comfort testing and surveys in residences have suffered from small sample size and not been representative of all socioeconomic and demographic classes; even surveys such as AHCS, RECS and RASS still struggle with definition of terms (e.g., programmable thermostat, setpoint, zones).

5. Energy savings from programmable thermostats

Programmable thermostats have been promoted (and mandated) as a means of saving energy. But programmable thermostats differ from the traditional conservation measures, such as insulation or a more efficient refrigerator, where simply installing the measure will save energy. In contrast, the occupants must actively program the thermostat and select settings that result in savings. Furthermore, observing the programmable thermostat-induced energy savings is experimentally difficult since energy savings cannot be observed directly; instead one must examine the *difference* in energy use between two periods. Few studies directly meter the gas for heating or electricity for cooling separately from other appliances. In addition, the differences in energy use may be partially attributable to differences with other appliance energy use, seasonal weather variations, or changes in occupants or economic conditions. Alternatively, one can measure the difference in energy use between similar homes with and without programmable thermostats. This approach is sometimes simpler but introduces other kinds of uncertainties. Perhaps these difficulties in evaluations explain why field studies of thermostat savings have shown mixed results.

One recent analysis of energy bills in about 7000 households concluded that savings of about 6% in natural gas consumption could be attributed to programmable thermostat use [61]. In Quebec, 90% of houses are electrically heated with room thermostats; a billing analysis study (more than 25,000 households) estimated that the use of programmable thermostats reduced the energy consumption by 3.6% [62]. In a survey conducted in Seattle with 2300 respondents, houses with programmable thermostats had on average a 9% reduction in electricity consumption [29]. Studies of cooling energy savings are less common.

Several field studies showed no significant savings in households using programmable thermostats compared to households using non-programmable thermostats [30,63–65]. Some of these studies are summarized in Table 1. The availability of a programmable thermostat did not change setback behaviors: people who were accustomed to setting back with a manual thermostat kept doing so, and did not increase their energy savings. Those who had not previously changed the temperature setpoints did not set back with programmable thermostats. Some researchers argued that homes relying on programmable thermostats consumed more energy than those where the occupants set the thermostats manually [66], especially with heat pumps [67].

The EPA reviewed these studies and concluded that consumers were not using programmable thermostats effectively due to programming difficulties and lack of understanding of terms such as setpoint [69]. As a result, the EPA discontinued the EnergyStar programmable thermostat program in December 2009.

Table 1
Summary of thermostat behavior and energy savings studies [68].

Organization	Investigators	Location & year	Sample size	Conclusions
Southern California Edison	Paul Reeves, Jeff Hirsch, Carlos Haiad	CA 2004	N/A	Energy savings depend on behavior and can be + or −
Energy Center of Wisconsin	Monica Nevius, Scott Pigg	WI 1999	299 Homes	No significant savings. PT's don't change behavior.
Connecticut Natural Gas Corporation	David Cross, David Judd	CN 1996	100 Homes	PT's cause no significant behavior change.
BPA/PNNL	Craig Conner	NW 2001	150 Homes	No significant behavior change/savings.
Florida Solar Energy Center	Danny Parker	FL 2000	150 Homes	No savings, some increases.

6. Usability issues

Programmable thermostats have not seen great market penetration; only about half are actually programmed to adjust temperatures at night or unoccupied times, and thus they do not necessarily save energy. The EPA review and other studies indicate that people find programmable thermostats difficult to understand, and lack the confidence and motivation to overcome difficulties in programming [64,70–74].

We recognize that there are many factors involved in people adopting and using a new device that are applicable; here we discuss Rogers' technology diffusion theory, Nielsen's factors of system acceptability, and usability guidelines.

Rogers' diffusion of innovation curve (Fig. 6) defines different attributes that affect the willingness and ability of consumers to trying new technology [75]. Rogers' theory describes why seemingly advantageous innovations, like the programmable thermostat, can take some time to diffuse in a social system. In some cases, policy has created a tipping point in driving adoption, especially between early adopters and the early majority; this has certainly been the case in California's higher adoption of programmable thermostats compared to the rest of the U.S.

Jakob Nielsen outlines factors in system acceptability, in Fig. 7. This figure is targeted for web interfaces, however, we feel it is applicable since thermostats are becoming more like other consumer electronics.

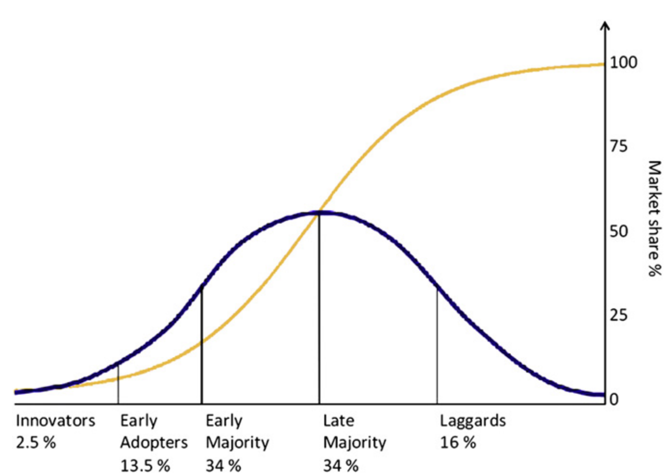

Fig. 6. Rogers' technology adoption or Diffusion of Innovation Curve [75].

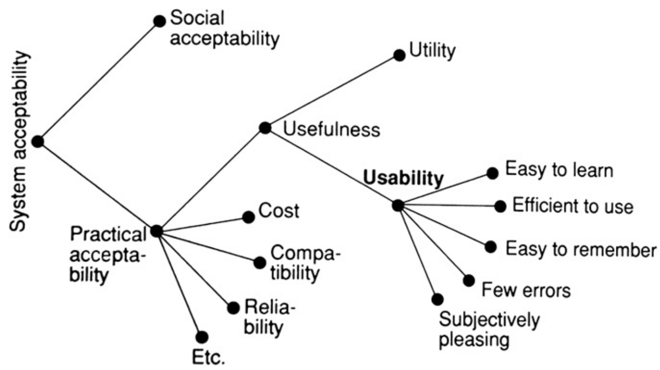

Fig. 7. Nielsens' factors in system acceptability [76].

In the International Organization for Standardization (ISO) Guidelines on Usability (ISO 9241-11 1998), usability refers to the extent to which a product can be used by specified users to achieve specified goals with *effectiveness* (the accuracy and completeness with which users achieve specified goals), *efficiency* (the resources expended in relation to the accuracy and completeness with which users achieve goals) and *satisfaction* (freedom from discomfort, and positive attitudes towards the use of the product) in a specified context of use [77]. In this section, we focus on some of issues mentioned in the literature on the use of programmable thermostats.

Our review of several U.S. and European studies collected a list of complaints and unexpected beliefs held by users on thermostats. Misconceptions about both energy and thermostats affect the use of thermostats, which arguably can be categorized under *social acceptability* in Nielsen's framework. Some people feel that heating all the time is more efficient than turning the heat off; in other words, they feel that turning down the thermostat for several hours per day actually consumes more energy because of the energy needed to heat the house back up to the comfort temperature [64,70]. Several studies have reported that consumers do not understand how their HVAC system works [36,78–82]. They may have incorrect mental models about creating comfortable indoor air temperature, especially since thermal feedback is delayed due to thermal inertia of the house. For example, they may think of the thermostat as an on–off switch or they may think the thermostat works as a valve: to accelerate heating, one must set the thermostat higher [80,83]. Many consumers do not know how much energy heating and cooling their home consumes or costs [70]. Other social acceptability issues may relate to priority of values: consumers may care about the environment, but value their comfort more [81,84]. In some cases, discomfort in entering a cold house discouraged people from lowering the temperature when they are away during the day [33]. In fact, in some countries a warm house is cozy and socially recognized [32]. Other social issues include gender differences in thermal perception or different needs and schedules of people in a household that make it more difficult to find agreement on the programmed temperature [53,54,80,81,85,86]. While some studies indicate residents found comfort in "fiddling" with their thermostats [35,60,87], other studies found that most people do not have interest in tinkering with their thermostats to optimize performance [38,78,88–90]. Other issues that are social in nature include a fear of the unknown: some people unfamiliar with a thermostat are afraid of using it in case there are terrible consequences [64,80,81,88].

The *practical acceptability* and *satisfaction* of using a programmable thermostat has many factors. Programmable thermostats cost more than manual thermostats, and consumers must expect enough value or *usefulness* (whether convenience, cost-savings, or some other *utility*) to warrant the time and money to purchase and install the new device. At least one study suggested that the payback and convenience are not worth the cost [64]. Other practical concerns include compatibility with the current system; there are a few anecdotal reports of people mounting their new programmable thermostat sideways to match the "footprint" of the old manual thermostat so they wouldn't need to repaint the wall. A few studies mention that the programmable thermostat was located in an inaccessible location [80,81]; many are located in hallways that are poorly lit. Current ADA standards require the placement of the thermostat 48 in. (1.2 m) above the floor which may be more usable for those in wheelchairs, but less usable for others than the 60 in. (1.5 m) de facto standard. In addition, many houses have alternative heating or cooling systems (e.g., woodstoves) not controllable by thermostats [64,81]. While many people have predictable schedules, others' schedules are more variable which makes the programming useless [64,81].

The poor *usability* of programmable thermostats and the necessity to improve their ergonomics was highlighted almost thirty years ago by Dale and Crawshaw, who stated that "it is easy to blame them [thermostat users] for stupidity, but is slowly being realized that the problem of efficiency in practice properly belongs to the engineers or the system designers" [91]. A report from 1982 illustrating the application of human factors techniques to heating controls interfaces listed several flaws, such as small text size and knobs, difficulties reading in poor lighting and distinguishing the current mode of the device, and lack of feedback on programming [92]. Although the technology of the interfaces has greatly improved over the past decades, little has been achieved in overcoming these problems.

One important aspect of usability is learnability: is operation of the device *easy to learn*? The EPA review and many other studies indicate that programmable thermostats are too complicated to use [33,64,71,73,74,80,81,83,93], especially for the elderly [73,81,88,94,95]. A consumer reports lab test stated that the subjects had difficulty setting the current time and day [71]; other studies indicate problems with programming desired temperature and schedule [33,64,81,94]. Several studies report that buttons and/or font size of text are too small [71,81,89,91,92]. Other studies point to poorly understood abbreviations (e.g., "Clk" for clock, "Prg" or "Prog" for program) and terminology (e.g., setpoint, program, default, zone) and confusing lights and symbols or icons [38,80,89,91,92].

Another aspect of usability is *efficiency*: how many steps does it take to achieve the objective? Boait and Rylatt reported the example of a thermostat that required a total of 28 steps to enter heating times, which were identical for each day of the week [74]. Freudenthal and Mook observed that programmable thermostat owners do not use all functions, even the ones they find valuable, due to poor interface design [94]. Several studies suggested that the layout of the interface itself was illogical, and thus difficult to navigate [89,91,92].

Since many thermostats at minimum require seasonal adjustment, the *easy to remember* factor of usability is important. Some thermostats have help or have a quick guide located on an inside cover. But many programmable thermostats require a manual, which can be 100+ pages long and are often unavailable when needed. Of the manuals themselves, Rathouse and Young reported that many people find them too technical, detailed and wordy, with not enough diagrams and attention on basics with procedural step-by-step instructions [81].

Another measure of usability is *few errors*. In a recent study in progress by one of the authors, Pritoni, nearly a fifth of households reported that the current time on their programmable thermostats was incorrect by more than an hour. Poor feedback in setting a program was listed in a few studies as leading to errors [80,92].

We only found one study that addressed the aesthetics of the programmable thermostat (is it *subjectively pleasing*?) as a barrier to usability [17]. Anecdotally, one author has heard many complain of the lack of aesthetics, especially in the vein of, “it just looks complicated, I don’t want to touch it.”

7. Discussion

Programmable thermostats have largely fallen short of the goal of saving consumers energy. Some research suggests that improving usability may increase use and adoption of programmable thermostats towards facilitating energy-saving behavior. This section describes what usability testing has been done and what more is needed as well as describing what new features may help usability.

7.1. Usability testing

Although a wide range of studies has been conducted on temperature settings, thermal comfort, and efficiency of HVAC systems, little quantitative information is available on how people deal with temperature and environmental controls. A few researchers have performed quantitative usability tests on programmable thermostats.

Karjalainen completed qualitative and quantitative surveys on thermostat use in homes and offices in Finland, and then developed a prototype thermostat interface with usability guidelines and a user-centered design approach [80]. As an example of user-centered methods, six focus groups were conducted in the UK [81] to investigate issues in use of heating controls. Based on user experiences and complaints, a series of recommendations for manufacturers and installers was formulated to improve the next generation of thermostat interfaces, including the recommendation that manufacturers offer a variety of products of different complexity to suit different needs.

Freudenthal and Mook [94] developed a programmable thermostat interface with vocal messages that guide the users through the programming steps, in order to provide an interface usable for people with no knowledge of the device, even for elderly users. The device usability was tested by videotaping the interactions with a touchscreen computer of 14 people randomly selected among the population of Delft.

Sauer et al. investigated various types of enhanced user support (status, history, predictive, instructional and warning displays) on user performance [95]. Seventy-five subjects were asked to evaluate them. The highest scoring interface was the predictive display, which predicted the impact of heating setups on certain parameters, such as energy consumption, efficiency, and comfort level, thus helping users make informed decisions [95]. The more interactive and rich information displays (e.g. warnings) appeared to be useful for less experienced people. The results of this study suggested that different levels of support were appropriate for specific situations and groups of users.

A recent publication by the UK Building Control Industry Association [96] focused on the implementation of user interfaces of control devices for heating, cooling, and ventilation, analyzing the flaws of existing interfaces and providing usability guidelines for new products. The authors affirmed that usable controls improved not only user satisfaction and comfort, but also they provided higher energy efficiency (use of HVAC only when needed), helped to building management (local control versus central control) and provided users with faster response of the system (due to perceived control and feedback).

To our knowledge, the only comparative usability study on commercially available programmable thermostats was conducted by Consumer Reports [71].[3] Twenty-five different thermostats were lab-tested to assess their energy performance and their usability. As a result, programmable thermostats were ranked according to these criteria and a series of problems with using thermostats were highlighted. Consumer reports did not explicitly state what parameters were considered to assess thermostat usability, and it did not appear that quantitative tests were performed. Moreover, the thermostats were tested in unusual conditions; namely, the users evaluated the thermostats while sitting down and in a well-illuminated room.

7.2. Recommendations

What features might increase adoption and usability of programmable thermostats? We discuss below some recommended features listed in the literature, as well as standards. The current trend in consumer electronics may help thermostat usability. Certainly adding thermostat functionality to existing interfaces, such as on the television or smart phone, may improve the use and usability. While home automation has been around for many years, perhaps today’s more compelling interfaces will encourage consumer acceptance of automation and intelligence in home controls. Educating consumers with better feedback may encourage programmable thermostat use, by revealing how much heating or cooling energy homes consume and how modifying the temperature setpoint can save energy.

Improved feedback: recently energy consumption feedback has received a great deal of attention [97–108] with respect to changing energy consumption behavior. Cost and energy consumption data can be obtained from interval meters, user-installed sensors on meters or appliances, smart appliances, and other intelligent systems. This information can help users understand the connection between temperature settings, HVAC use, cost, and the environment. Some recent studies indicate that the estimated time expected to reach the selected temperature is a useful indication for users [17,80]. This feature may also enhance the users’ perception of control of the system and discourage the use of the thermostat as if it were a valve.

Intelligent systems: automated systems can, in theory, limit the need for human interaction, such as eliminating thermostat programming by systems that learn occupancy schedules and thermal preference. Different solutions have been suggested to monitor the location of household members ranging from occupancy sensors [57,109–112] to Mobile GPS [17]. Occupancy data can also be predicted from historic energy consumption [74]. Sensors can be complemented by an intelligent controller that uses learning algorithms to recognize patterns (e.g., preference in temperatures and characteristics of HVAC and house) [57,74,113]. Intelligent systems can theoretically overcome some of the problems associated with human-thermostat interaction, although some users may be reluctant to surrender control. Clearly the optimal path is to provide choices in the balance between user control and automated features [57].

Communication: the thermostat can use a home gateway to communicate with other devices in a Home Area Network such as smart appliances, in home energy displays, and energy detectors. A thermostat could in theory exchange data with utilities and other service providers. Web/mobile interfaces already enable the control

[3] While programmable thermostat manufacturers affirm they perform usability tests for their products, they do not disclose results because they consider the user interface a key feature for sales.

of thermostat configurations from personal computers, cell phones, and potentially Internet-connected television. Enhanced communication with other devices in the home and with the outside world may increase thermostat usability by piggybacking on other devices with more interesting and provocative user interfaces that are easy to use.

Other improvements: voice-controlled thermostats, such as by Talking Thermostats.com and Innotech, may improve thermostat usability for elderly or motion-disabled people [114,115]. Voice-activated devices could dramatically simplify the interaction with thermostats, especially in case of out-of-schedule requests [81]. Some researchers have proposed the development of goal-setting strategies for occupant interactions with programmable thermostats [85]. Some studies have suggested new functions considered useful to consumers. One is a "boost button" (an additional hour of heating or cooling) [81], similar to the plus-1-minute button commonly found on microwave ovens. This function could provide flexibility to a programmed schedule; in other words, a single button press could extend the space conditioning to accommodate an impromptu change in schedule. In the same vein, another potential function is a timer [90] to turn on or off heating or cooling for a specific amount of time. A third helpful function is an estimation of the time needed to reach the desired temperature [80]. These features are not currently available in any of the surveyed U.S. thermostats. In response to demands to simplify the interfaces, a single button push triggering an energy-saving mode has been proposed in EnergyStar Program Requirements. Aesthetically improved interfaces are suggested by several studies to improve social acceptability and increase likelihood of adoption. Another area of improvement is motivation: the "Green Machine" [116] is a mobile application that is an example of *persuasive technology*—defined by BJ Fogg as technology created for the purpose of changing people's attitudes or behaviors [117]. The Green Machine interface provides a visualization of energy consumption in comparison to user goals and utilizes social networking to motivate users to reduce their energy consumption.

In the long term, standardization can improve usability, because people have to learn a system only once. In our survey of thermostats currently available in the market we found a substantial lack of standardization not only in the interaction design, but also in symbols, icons, and text. The most basic functions and concepts are implemented in different ways. Standardization of interfaces, symbols, and icons has been successfully implemented in other sectors such as in car dashboards (SAE Standards [118]) and in power controls for electronic equipment (IEEE 1621 [119]).

7.3. Future work

We suggest that a "good" thermostat design is not only usable (easy to use/learn/remember), but also useful (provides needed functions for its users) in a way that is cost-effective and compatible with existing equipment. Arguably, a good programmable thermostat would facilitate energy-saving behavior as well as provide comfort and convenience for the people using it. But do thermostats really save energy? What else factors into their adoption and use? And what is good usable design? To whom?

We recognize several needed areas of research. Additional research is needed to determine the energy savings from programmable thermostats and link the amount of savings to initial conditions and usage of the thermostat's features. In addition, we uncovered little exploration of thermal comfort in homes; this is well studied in commercial buildings and has led to better control strategies. Understanding residential thermal comfort could improve comfort and save energy. Another issue entirely is addressing motivation to use the thermostat to save energy. Are there softer non-technical means of achieving the same goals, for example, with social networking with Facebook or encouraging behavior change by promoting positive social norms in utility bill inserts?

At the beginning of this section we listed the few quantitative usability studies we could find. While a few surveys and some studies point anecdotally to widespread user difficulties with programmable thermostats, the literature contains relatively few usability studies with quantitative data and analysis. (Access to the thermostat manufacturers' consumer telephone help lines would be invaluable.) Lack of usability studies is a critical weakness in the design of advanced thermostats because usability is among the most frequent complaints about them.

We have begun some initial exploratory usability studies which are described in [120]. We think that there is not a "one-size fits all" solution; we are exploring the elements of good thermostat design, and are currently outlining design principles of programmable thermostats. While we briefly mention technology adoption theory and guidelines for web user interface design in this review, we plan further research to look at usability in other fields, such as medical equipment and dashboards.

8. Conclusion

Thermostats play a vital role in both providing comfort to people in their homes and controlling the most energy intensive systems in the home—heating and cooling. This review began with a brief history of the thermostat, outlined the basic features, discussed ownership and use of manual and programmable thermostats in the U.S., described the energy savings—or rather lack thereof—and pointed out usability issues. Our review of thermostats indicates that the thermostats designed and promoted by energy conservation policies have had slow penetration into the market and are used as designed in only half of the homes in the U.S. In general, the energy savings from using programmable thermostats are less than predicted, although we acknowledge that these evaluations are difficult to perform.

The number and variety of new features for programmable thermostats is increasing, which further complicates the device. One example is the programmable communicating thermostat for residential demand response. Many utilities are exploring time-varying price tariffs to reduce peak electricity demand—driven primarily from space heating and cooling. Yet, overlaying price-response on the current functionality of programmable thermostats will only increase the complexity of this already misunderstood and underutilized device, much less introduce a tariff structure completely foreign to many consumers.

User complaints culled from the literature include misconceptions about energy use and how thermostats work, lengthy and obtuse operating manuals, and social and practical barriers to using programmable thermostats. The user misconceptions are particularly important since they may encourage incorrect usage that cannot be easily overcome by better interfaces. When users complained about the thermostats themselves, they noted in particular their complexity, small size of buttons and text, confusing terms and symbols, and the number of steps needed to program the devices.

Several studies indicated disparate attitudes towards thermostats. Some users preferred never to adjust their thermostats—to the point of being afraid of touching them; some believe that changes in thermostat settings consume more energy. Others tinkered with their thermostat several times per day, and prefer the control of manual adjustment to a set program. These groups will have different priorities for top-level features.

Our recommendations for improved usability include access through a web portal and use of audible commands and even voice recognition. The literature revealed some functions that would be desirable to some users but are not available in U.S. models, such as a "boost" feature that would provide an extra hour of operation (similar to the "plus one minute" feature on a microwave oven). One study found that users liked a feature that would indicate how long it would take to achieve the desired temperature.

A goal of future thermostats will be to overcome the misconceptions about thermostat operation and to minimize the number of interface-related complaints. At present, however, designers lack the foundational research to determine which thermostat features succeed or fail. We are encouraged by EnergyStar's inclusion of usability metrics in the future thermostat specification and hope that this effort leads to more quantitative usability research as well as building on the success of intuitive popular consumer electronics.

Finally, we note that the thermostat is only one of many devices where human interaction plays a role in energy consumption. We expect a similar discourse in the future on in-home energy displays, lighting controls, as well as household appliances (such as televisions) that focus on making energy consumption more transparent and user interfaces more usable.

Acknowledgements

We wish to thank Jessica Granderson, Dhawal Mujumdar, Becky Hurwitz and Margarita Kloss for their contributions, Bruce Nordman for providing comments and input on a review draft of this study, and Iain Walker, who was a co-author of an earlier report from which we drew. In addition, we thank the California Energy Commission for early support through a closely related project.

We gratefully acknowledge the support of the Office of Energy Efficiency and Renewable Energy, Building Technologies Program, of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

References

[1] Residential energy consumption survey: preliminary housing characteristics tables. Energy Information Administration (EIA). Available from: http://www.eia.doe.gov/emeu/recs/recs2005/hc2005_tables/detailed_tables2005.html; 2005 [accessed June 21, 2010].
[2] Residential energy end-use splits by fuel type (quadrillion BTU). Table 2.1.5. U.S. Department of Energy (DOE). Available from: http://buildingsdatabook.eren.doe.gov/ChapterIntro2.aspx?2#1; 2008 [accessed April 6, 2011].
[3] Figure 2.5 household energy consumption and expenditures, consumption by end use, 2005. Annual energy review. Energy Information Administration (EIA). Available from: http://www.eia.gov/aer/consump.html; 2009 [accessed Dec. 1, 2010].
[4] Brown RE, Koomey JG. Electricity use in California: past trends and present usage patterns. Berkeley: Lawrence Berkeley National Laboratory; 2002. LBL-47992.
[5] U.S. Census Bureau. Characteristics of Housing. Available from: http://www.census.gov/const/www/charindex.html; 2009.
[6] Table 1.1 primary energy overview, 1949–2009. Energy Information Administration (EIA). Available from: http://www.eia.doe.gov/totalenergy/data/annual/txt/ptb0101.html; 2010 [accessed 25 May 2011].
[7] Schwartz K. Striving for simpler, smarter T-stats. The air conditioning heating refrigeration news; Sept. 20, 2010. Available from: http://digital.bnpmedia.com/display_article.php?id=498766.
[8] Meier AK, Walker I. Residential thermostats: comfort controls in California homes. Berkeley: Lawrence Berkeley National Laboratory; 2008. LBNL938E.
[9] Hypocaust. Encyclopedia Britannica online; Feb. 3, 2011. Available from: http://www.britannica.com/EBchecked/topic/279869/hypocaust#.
[10] History and construction of the thermometer. Scientific American Feb. 3, 2011;5(50):395. Available from: http://memory.loc.gov/cgi-bin/query/r?ammem/ncps:@field%2528DOCID+@lit%2528ABF2204-0005-51%2529%2529::1850.
[11] Johnson controls; Feb. 3, 2011. Available from: www.johnsoncontrols.com/publish/us/en/about/history.html.
[12] Honeywell. Our history; Feb 3, 2011. Available from: http://honeywell.com/About/Pages/our-history.aspx.
[13] Nelson LW, MacArthur JW. Energy savings through thermostat setbacks. ASHRAE Transactions 1978;83:319–33.
[14] U.S. Department of Justice. ADA standards for accessible design, 28 CFR part 36. Codes of Federal Regulations; 1994.
[15] Environmental Protection Agency (EPA). Programmable thermostats web page; 2009. http://www.energystar.gov/index.cfm?fuseaction=find_a_product.showProductGroup&pgw_code=TH.
[16] Environmental Protection Agency (EPA). Draft 2 version 1.0 specification for climate controls webinar; Feb. 23, 2011. Available from: http://www.energystar.gov/index.cfm?c=new_specs.climate_controls.
[17] Gupta M, Intille S, Larson K. Adding GPS-control to traditional thermostats: an exploration of potential energy savings and design challenges. Pervasive Computing; 2009:95–114.
[18] U-SNAP alliance; Dec. 16, 2010. Available from: http://www.usnap.org/.
[19] Borenstein S, Jaske M, Rosenfeld A. Dynamic pricing, advanced metering, and demand response in electricity markets. Berkeley Center for the Study of Energy Markets, University of California Energy Institute; 2002.
[20] Honeywell round thermostat image; May 31, 2011. Available from: http://www.americanallergysupply.com/cleanair-stat.htm.
[21] LUX 1500 thermostat; May 31, 2011. Available from: http://aircusa.com/index.php?option=com_virtuemart&page=shop.browse&category_id=31&Itemid=26.
[22] White Rodgers, White Rodgers thermostat; May 31, 2011. Available from: http://whiterodgersthermostats.org/.
[23] Amundson JB, Vick BD, Bergman GA, Finch HJ. Programmable controller with saving changes indicator. U.S. patent no. US 7,274,972 B2. Honeywell International Inc.; 2007.
[24] Energy Information Administration (EIA). Residential energy consumption survey, housing characteristics tables, table HC15.7: air-conditioning usage; June 21, 2010. Available from: http://www.eia.doe.gov/emeu/recs/recs2005/hc2005_tables/hc7airconditioningindicators/pdf/tablehc15.7.pdf.
[25] Energy Information Administration (EIA). Residential energy consumption survey, housing characteristics tables, table HC14.5: space heating usage; Feb. 16, 2011. Available from: http://www.eia.gov/emeu/recs/recs2005/hc2005_tables/detailed_tables2005.html.
[26] California Energy Commission (CEC). California statewide residential appliance saturation study. Sacramento: California Energy Commission; 2004.
[27] Energy Information Administration (EIA). Data quality; Feb. 16, 2011. Available from: http://www.eia.doe.gov/emeu/recs/recs2001/appendixb.html.
[28] Decision Analyst. 2008 American home comfort survey. Arlington: Decision Analyst; 2008.
[29] Tachibana D. Residential customer characteristics survey; 2009. Available from: www.cityofseattle.net/light/Conserve/Reports/Evaluation_15.pdf. Sept 23, 2010.
[30] Haiad C, Peterson J, Reeves P, Hirsch J. Programmable thermostats installed into residential buildings: predicting energy savings using occupant behavior & simulation. Southern California Edison; 2004.
[31] Woods J. Fiddling with thermostats: energy implications of heating and cooling set point behavior. Proceedings of the 2006 ACEEE summer study on energy efficiency in buildings; 2006.
[32] Wilhite H, Nakagami H, Masuda T, Yamaga Y, Haneda H. A cross-cultural analysis of household energy use behaviour in Japan and Norway. Energy Policy 1996;24:795–803.
[33] Linden A-L, Carlsson-Kanyama A, Eriksson B. Efficient and inefficient aspects of residential energy behaviour: what are the policy instruments for change? Energy Policy 2006;34:1918–27.
[34] Archacki R. Carrier thermostat mode summary: summer 2003. (personal correspondence to Gaymond Yee); 2003.
[35] Hackett B, McBride R. Human comfort field studies. Sacramento: California Energy Commission; 2001.
[36] Kempton W, Krabacher S. Thermostat management: intensive interviewing used to interpret instrumentation data. In: Kempton W, Neiman M, editors. Energy efficiency: perspectives on individual behavior. Berkeley: American Council for an Energy Efficient Economy; 1987. p. 245–62.
[37] Lutz J, Wilcox BA. Comparison of self reported and measured thermostat behavior in new California houses. Proceedings of the 1990 ACEEE Summer Study on Energy Efficiency in Buildings 1990;2:91–100.
[38] Lutzenhiser L. A question of control: alternative patterns of room air-conditioner use. Energy and Buildings 1992;18:192–200.
[39] Weihl JS, Gladhart PM. Occupant behavior and successful energy conservation: Findings and implications of behavioral monitoring. Proceedings of the 1990 ACEEE Summer Study on Energy Efficiency in Buildings 1990;2:171–80.
[40] Ubbelohde MS, Loisos G, McBride R. Advanced comfort criteria & annotated bibliography on adapted comfort. Sacramento: California Energy Commission; 2003.
[41] Fishman DS, Pimbert SL. Some recent research into home heating. Journal of Consumer Studies and Home Economics 1981;5:1–12.
[42] Residential tenants heat and hot water. NYC Department of Housing Preservation & Development. Available from: http://www.nyc.gov/html/hpd/html/tenants/heat-and-hot-water.shtml; 2010 [accessed Feb. 17, 2011].
[43] Lovins A. Air conditioning comfort: behavioral and cultural issues. Boulder: ESource; 1992.
[44] Fanger PO. Thermal comfort. Copenhagen: Danish Technical Press; 1970.
[45] Leaman A, Bordass B. Assessing building performance in use 4: the probe occupant surveys and their implications. Building Research and Information 2001;29:129–43.

[46] Arens E, Xu T, Miura K, Zhang H, Fountain M, Bauman F. A study of occupant cooling by personally controlled air movement. Energy and Buildings 1998; 27:45–59.
[47] Humphreys MA, Nicol JF. The validity of ISO-PMV for predicting comfort votes in every-day thermal environments. Energy and Buildings 2002;34: 406–30.
[48] de Dear RJ, Brager GS. Developing an adaptive model of thermal comfort and preference. ASHRAE Transactions 1998;104:145–67.
[49] Brager GS, Paliaga G, de Dear RJ. Operable windows, personal control, and occupant comfort. ASHRAE Transactions 2004;110:17–35.
[50] American Society for Heating Refrigerating and Air-Conditioning Engineers (ASHRAE). Standard 55-2004: thermal environmental conditions for human occupancy. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.; 2004.
[51] Nicol JF, Humphreys MA. New standards for comfort and energy use in buildings. Building Research & Information 2009;37:68–73.
[52] van Hoof J, Kort HSM, Hensen JLM, Duijnstee MSH, Rutten PGS. Thermal comfort and the integrated design of homes for older people with dementia. Building and Environment 2010;45:358–70.
[53] Karjalainen S. Gender differences in thermal comfort and use of thermostats in everyday thermal environments. Building and Environment 2007;42: 1594–603.
[54] Beshir MY, Ramsey JD. Comparison between male and female subjective estimates of thermal effects and sensations. Applied Ergonomics 1981;12: 29–33.
[55] Brager GS, de Dear RJ. Thermal adaptation in the built environment: a literature review. Energy and Buildings 1998;27:83–96.
[56] Humphreys MA, Nicol JF. Understanding the adaptive approach to thermal comfort. ASHRAE Transactions: Symposia 1998;104:991–1004.
[57] Peffer TE. California DREAMing: the design of residential demand responsive technology with people in mind. Berkeley: University of California Berkeley; 2009.
[58] Bae C, Chun C. Research on seasonal indoor thermal environment and residents' control behavior of cooling and heating systems in Korea. Building and Environment 2009;44:2300–7.
[59] Stein B, Reynolds JS. Mechanical and electrical equipment for buildings. New York: John Wiley & Sons, Inc.; 1992.
[60] Home air conditioning test survey. Emerson Climate Technologies; 2004. Available from: http://www.gotoemerson.com.
[61] RLW Analytics. Validating the impact of programmable thermostats. Middletown, CT: GasNetworks; 2007.
[62] Michaud N, Megdal L, Baillargeon P, Acocella C. Billing analysis & environment that "re-sets" savings for programmable thermostats in new Homes, 2009, IEPEC. Portland.
[63] Cross D, Judd D. Automatic setback thermostats: measure persistence and customer behavior. Chicago: IEPEC; 1997.
[64] Nevius M, Pigg S. Programmable thermostats that go berserk: taking a social perspective on space heating in Wisconsin. Proceedings of the 2000 ACEEE Summer Study on Energy Efficiency in Buildings; 2000:8.233–44.
[65] Shipworth M, Firth SK, Gentry MI, Wright AJ, Shipworth DT, Lomas KJ. Central heating thermostat settings and timing: building demographics. Building Research & Information 2010;38:50–69.
[66] Sachs H. Programmable thermostats. Washington, D.C: American Council for an Energy Efficient Economy; 2004.
[67] Bouchelle MP, Parker DS, Anello MT. Factors influencing space heat and heat pump efficiency from a large-scale residential monitoring study. Proceedings of the 2000 ACEEE summer study on energy efficiency in buildings; 2000.
[68] Shiller D. Programmable thermostat program proposal. U.S. EPA; 2006.
[69] Harris AD. EnergyStar is examining thermostat approach: Air conditioning, heating and refrigeration NEWS; 2008.
[70] Rathouse K, Young B. Market transformation programme – domestic heating: use of controls; 2004. Available from: http://efficient-products.defra.gov.uk/ReferenceLibrary/Domestic_Heating_Controls_RPDH15.pdf [accessed June 21, 2010].
[71] Consumer reports. Programmable thermostats lab test – some make saving easier; 2007. Available from: http://www.consumerreports.org/cro/appliances/heating-cooling-and-air/thermostats/thermostats-10-07/overview/therm-ov.htm [accessed June 21, 2010].
[72] Karjalainen S, Koistinen O. User problems with individual temperature control in offices. Building and Environment 2007;42:2880–7.
[73] Critchley R, Gilbertson J, Grimsley M, Green G, Warm Front Study Group. Living in cold homes after heating improvements: evidence from Warm-Front, England's home energy efficiency scheme. Applied Energy 2007;84: 147–58.
[74] Boait PJ, Rylatt RM. A method for fully automatic operation of domestic heating. Energy and Buildings 2010;42:11–6.
[75] Rogers EM. Diffusion of innovations. New York: Free Press; 2003.
[76] Nielsen J. Usability engineering. San Francisco: Morgan Kaufmann; 1993.
[77] Guidance on usability, 9241-11:1998. Geneva: International Organization for Standardization (ISO); 1998.
[78] Diamond RC, Remus J, Vincent B. User satisfaction with innovative cooling retrofits in sacramento public housing. Proceedings of the 1996 ACEEE summer study on energy efficiency in buildings; 1996.
[79] Karjalainen S. Thermal comfort and use of thermostats in Finnish homes and offices. Building and Environment 2009;44:1237–45.
[80] Karjalainen S. The characteristic of usable room temperature control. Helsinki University of Technology; 2008.
[81] Rathouse K, Young B. RPDH15: use of domestic heating controls. Watford: Building Research Establishment (UK); 2004.
[82] Kempton W. Two theories of home heat control. Cognitive Science 1986;10: 75–90.
[83] Vastamaki R, Sinkkonen I, Leinonen C. A behavioural model of temperature controller usage and energy saving. Personal Ubiquitous Comput. 2005;9: 250–9.
[84] Pedersen M. Segmenting residential customers: energy and conservation behaviors. Proceedings of the 2008 ACEEE Summer Study on Energy Efficiency in Buildings 2008;7:229–41.
[85] McCalley L, Midden C. Goal conflict and user experience: moderators to the use of the clock thermostat as a device to support conservation behavior. Proceedings from the 2004 ACEEE Summer Study on Energy Efficiency in Buildings 2004;7:251–9.
[86] Parker D, Barkaszi S, Sherwin J, Richardson C. Central air conditioner usage patterns in low-income housing in a hot and humid climate: influences on energy use and peak demand. Proceedings from the 1996 ACEEE Summer Study on Energy Efficiency in Buildings 1996;8:147–60.
[87] Kempton W, Reynolds C, Fels M, Hull D. Utility control of residential cooling: resident-perceived effects and potential program improvements. Energy and Buildings 1992;18:201–19.
[88] Diamond RC. Comfort and control: energy and housing for the elderly. Environmental Design Research Association 15. San Luis Obispo, California: Environmental Design Research Association; 1984.
[89] Diamond RC. Energy use among the low-income elderly: a closer look. Proceedings of the 1984 ACEEE summer study on energy efficiency in buildings; 1984b.
[90] Kempton W, Feuermann D, McGarity AE. "I always turn it on super": user decisions about when and how to operate room air conditioners. Energy and Buildings 1992;18:177–91.
[91] Dale HCA, Crawshaw CM. Ergonomic aspects of heating controls. Building Services Engineering Research and Technology 1983;4:22–5.
[92] Moore TG, Dartnall A. Human factors of a microelectronic product: the central heating timer/programmer. Applied Ergonomics 1982;13:15–23.
[93] Fujii H, Lutzenhiser L. Japanese residential air-conditioning: natural cooling and intelligent systems. Energy and Buildings 1992;18:221–33.
[94] Freudenthal A, Mook HJ. The evaluation of an innovative intelligent thermostat interface: universal usability and age differences. Cognition, Technology & Work 2003;5:55–66.
[95] Sauer J, Wastell DG, Schmeink C. Designing for the home: A comparative study of support aids for central heating systems. Applied Ergonomics 2009; 40:165–74.
[96] Bordass B, Leaman A, Bunn R. Controls for end users a guide for good design and implementation; 2007. Available from: http://www.usablebuildings.co.uk/Pages/UBPublications/UBPubsControlsForEndUsers.html [accessed Sept. 23, 2010].
[97] Lutzenhiser L. Social and behavioral aspects of energy use. Annual Review of Energy and Environment 1993;18:247–89.
[98] Bell PA, Greene TC, Fisher JD, Baum A. Environmental psychology. Fort Worth: Harcourt Brace College Publishers; 1996.
[99] Egan C, Kempton W, Eide A, Lord D, Payne C. How customers interpret and use comparative graphics of their energy use. Proceedings of the 1996 ACEEE summer study on energy efficiency in buildings; 1996.
[100] Darby S. Making it obvious: designing feedback into energy consumption. Oxford: Environmental Change Institute; 2000.
[101] Darby S. The effectiveness of feedback on energy consumption. Oxford: Environmental Change Institute; 2006.
[102] Stein LF, Enbar N. Direct energy feedback technology assessment for Southern California Edison Company. Boulder: EPRI Solutions; 2006.
[103] Wood G, Newborough M. Energy-use information transfer for intelligent homes: enabling energy conservation with central and local displays. Energy and Buildings 2007;39:495–503.
[104] Allen D, Janda K. The effects of household characteristics and energy use consciousness on the effectiveness of real-time energy use feedback: a pilot study. Proceedings of the 2006 ACEEE Summer Study on Energy Efficiency in Buildings 2006;7:1–12.
[105] Wood G, Newborough M. Dynamic energy-consumption indicators for domestic appliances: environment, behaviour and design. Energy and Buildings 2003;35:821–41.
[106] Neenan B, Robinson J, Boisvert RN. Residential electricity use feedback: a research synthesis and economic framework. Electric Power Research Institute (EPRI); 2009.
[107] Anderson W, White W. The smart way to display. UK: Energy Saving Trust; 2009.
[108] Fischer C. Feedback on household electricity consumption: a tool for saving energy? Energy Efficiency 2008;1.
[109] Fountain M, Brager G, Arens E, Bauman F, Benton C. Comfort control for short-term occupancy. Energy and Buildings 1994;21:1–13.
[110] BAYweb; June 21, 2010. Available from: http://www.bayweb.com/.
[111] RCI automation; June 21, 2010. Available from: http://www.rciautomation.com/thermostat_occupancy.htm.

[112] Telkonet; June 21, 2010. Available from: http://www.telkonet.com/products/energy_management.php.
[113] Moon JW, Kim J- J. ANN-based thermal control models for residential buildings. Building and Environment 2010;45:1612–25.
[114] Innotech System Inc.; June 21, 2010. Available from: http://www.innotechsystems.com/voice.htm.
[115] Talking thermostats;. June 21, 2010. Available from: http://www.talkingthermostats.com/blind.shtml.
[116] Marcus A, Jean J. Going green at home: the green machine. Information Design Journal 2009;17:235–45.
[117] Fogg BJ. Persuasive technology: using computers to change what we think and do. Morgan Kaufmann; 2002.
[118] SAE International. Standards (automotive); Feb. 24, 2011. Available from: http://standards.sae.org/.
[119] Nordman B, McMahon J, Meier AK. IEEE 1621: power control user interface. Lawrence Berkeley National Laboratory. Available from: http://eetd.lbl.gov/Controls/1621/; 2004 [accessed Feb. 24, 2011].
[120] Meier AK, Aragon C, Peffer T, Perry D, Pritoni M. Usability of residential thermostats: preliminary investigations. Building and Environment 2011;46:1891–8.