Title

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ABSTRACT

Digital and physical prototypes are commonly used across a broad range of industries for product development and user experience testing. Prototyping processes are also used in scientific research to generate ideas and test hypotheses. However, these creative activities receive less attention in research papers than the quantitative methods and findings. This paper describes a resourceful and iterative process of building, refining and testing a variety of ‘personal comfort devices’ that were used in a series of research studies in labs and in occupied non-residential buildings. The studies demonstrated that when building users have the ability to individualize their thermal environments, they can accept wider temperature ranges, potentially leading to reductions in HVAC energy consumption while also improving comfort. The devices tested include office chairs with battery-powered heating and cooling, IoT-connected desk fans and low-energy heating devices. This paper describes the ‘scrappy’ prototyping work that enabled this research, placing it within a context of prototyping theory. Without the highly developed prototypes created by the researchers, it would not have been possible to make the quantitative changes to building standards that are needed to influence practice.

Introduction

Prototyping has become a ubiquitous part of the development cycle of many products, services and processes. In scientific research, *ad hoc* prototyping also plays an important role, however, researchers may not be familiar with advanced prototyping practices that could make these activities more effective. This paper describes a series of research studies that advanced innovative approaches to reducing energy use in non-residential buildings, and which relied on the creation of numerous prototypes. These are described *post hoc* within a context of prototyping theory, in order to elucidate best practices for the future application of prototypes to scientific inquiry.

Several efforts have been made to offer a taxonomy of prototypes based on the level of refinement, on the purpose of the prototypes, and on differentiation between physical forms versus functions. One such framework, a multi-level matrix for physical prototypes, outlines process aspects such as communication, evaluation purpose, cost, and design stage. The matrix also outlines physical characteristics such as prototype size, material and fabrication method (Michaelraj 2009).

Prototyping can be useful to serve multiple goals, including the refinement of a design, communication, exploration, and active learning (Camburn et al. 2017). Prototypes may be used to inform the experience of the design team, to reframe failures as learning, to document a design progress, and to help manage ambiguity (Gerber and Carroll 2012). The prototyping process frequently follows a serial process, in which a concept is moved forward through a series of trials and iterations. However, advancing multiple paths in parallel has been shown effective for avoiding fixation, generating more diverse solutions, and endowing designers with more confidence about their work (Dow et al. 2010).

Prototypes can range from low fidelity versions to highly refined ones that closely resemble a final product. The term 'product mockups' describes rapidly made, low cost approximations. These quickly demonstrate a concept, and are especially useful for communication 'and to make ideas concrete' (Camburn et al. 2017). Also, virtual prototypes may be more rapidly iterated than physical prototypes. In today's workflows using additive manufacturing (3D printing) the gap between virtual and physical prototypes has been narrowed, as a virtual model can be rapidly be made real, informing the design and allowing for more rapid iteration and refinement

Prototyping for Research and Thermal Comfort Innovations

The literature cited above describes applications of prototypes for user experience testing and product development, based on examples from numerous industries. However, similar iterative prototyping processes are commonly required for scientific research, and many successful academic research groups have robust 'maker' capabilities. Wensveen and Matthews (2014) describe several roles for prototyping in research. These include prototypes as 'instruments of inquiry,' the scientific act of collecting, measuring and recording phenomena. The authors also describe the use of prototypes as 'research architypes,' which are 'physical embodiments of concepts, understandings or design spaces that can be argued to constitute contributions to the discipline.'

Such prototyping activities were central to a multi-year research program on personal comfort systems (PCS) led by faculty and researchers at UC Berkeley's Center for the Built Environment (CBE). The studies demonstrated that when building users have the ability to individualize their thermal comfort, they are accepting of wider temperature ranges, leading to potential reductions in HVAC energy consumption while also improving comfort (Zhang et al. 2010, Bauman et al. 2017). This work created and tested numerous prototypes of IoT-connected desk fans, low-energy footwarmers, office chairs with battery-powered heating and cooling, and other devices, many having advanced research capabilities including data collection, wireless communication and wireless battery charging.

The concept behind individual comfort control is based on key findings from previous research. First, a significant percentage of non-residential building users are not satisfied with thermal comfort. Analysis of occupant survey data shows that most buildings fail to reach the ASHRAE requirement of providing thermal satisfaction for 80% of a building's population. Survey data from 351 buildings and over 50,000 individuals shows that only 38% of occupants are satisfied with thermal comfort. The percentage of buildings meeting the 80% satisfied criteria is only 2% if one considers responses from 'slightly satisfied to very satisfied,' and only 8% if one includes additional responses of 'neutral' (Karmann et al. 2018). The low satisfaction is partially explained by studies showing that thermal preference varies between individuals by as much as 5°F (3°C) (Luo et al. 2019). The obvious conclusion is that no single indoor thermal condition suits all building users.

Secondly, maintaining narrow indoor temperature ranges results in significant energy use. Relaxing temperature ranges ('dead bands' between heating and cooling set points) may save significant amounts of energy with little or no impact on thermal comfort. While results are highly climate dependent, energy simulations indicate that in North American office buildings, an increase of the cooling setpoint of 5°F (3°C) may save 27% of total HVAC energy on average. Reducing the heating setpoint by only 2°F (1°C) saves an average of 34% of terminal heating energy, and these cooling and heating savings are generally additive (Hoyt et al. 2014). Findings from these studies challenge conventional HVAC approaches based on a narrow range of indoor temperatures stipulated by comfort standards, which have remained largely unchanged since they were adopted many decades ago. Recent research also shows that narrow temperature ranges do not improve thermal comfort (Li et al. 2019).

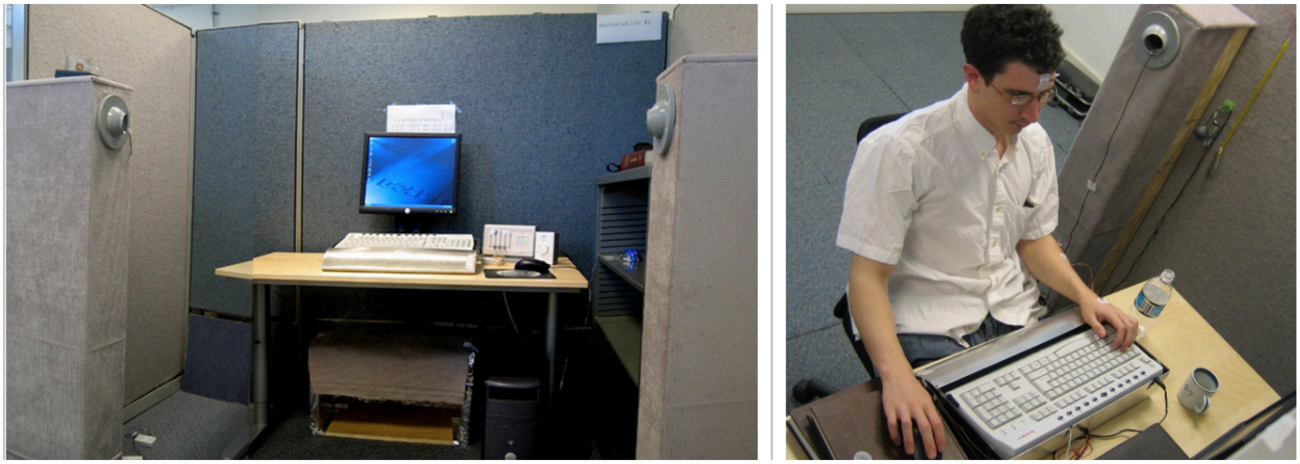
Such findings provide the motivation to study and encourage the adoption of personal comfort systems. A few examples of commercially available personal comfort systems have been studied, for example the Personal Environmental Modules (PEMs) produced by Johnson Controls, intended for integration with underfloor air distribution systems. A field study showed that all subjects with the PEMs reported satisfaction with thermal comfort, suggesting that individualized thermal comfort control holds great promise (Bauman et al. 1997).

Phase One: Laboratory Studies with Low-Fidelity Prototypes

Thermal sensation and comfort are described both in terms of individual body parts and for the body overall. Overall comfort is influenced more by some body parts than by others. In warm environments the head and 'breathing zone' are most critical, and the extremities are important in cool conditions (Arens, Zhang, and Huizenga 2005).

Consequently, the CBE research team reasoned that most efficient PCS devices — those that would deliver the greatest comfort with the least energy use — would focus on cooling the face and head in warm conditions, and warming hands and feet in cool conditions.

This concept was pursued in the first generation of PCS devices, initially referred to as task/ambient conditioning (TAC). These were tested in a laboratory setting using low- and medium-fidelity prototypes as shown in Figures 1a-b. The test conditions included: (1) a baseline with no PCS devices; (2) with PCS devices set to pre-determined settings; and (3) with PCS devices having control given to subjects (Zhang et al. 2010). For warm environments, subjects were provided with cooling towers located on each side of the body, and also cooling from small fans built into keyboards. Each cooling tower was fitted with adjustable air nozzles that the researchers focused on subjects' cheeks and breathing zones (and not into their faces to prevent dry-eye discomfort), with small 35-watt fans supplying either cool or re-circulated room air. The hand cooling was provided by three 2-watt fans fitted into keyboard tray prototypes fabricated from acrylic and aluminum sheets. For cool environments, the researchers created footwarmer prototypes, using well insulated boxes with reflective foil linings, each having a 125-watt heat lamp focused on the top of the subjects' feet. While these initial low-fidelity devices were designed and created quickly, this general concept was retained later, even after significant exploration, as described below. Palm warmers were created to fit the keyboard trays, created from aluminum and curved to a shape similar to commercial wrist rests. Electrical heating tape below the aluminum provided a warm surface of 95ºF (35ºC). Commercially available heated keyboard trays and mice were also tested. Finally, user controls were prototyped using standard rheostats and repurposed control panels from Johnson Controls PEM units left over from earlier studies.



Figures 1a-b. Low- and medium-fidelity prototypes for phase-one PCS tests included cooling towers, footwarmers, keyboard heating/cooling and wrist warmers. Subjects' user controls are seen to the right of the keyboard.

Phase one study results. With PCS devices the subjects found their environments to be thermally comfortable across a wide range of temperatures from 65 to 86ºF (18 to 30 ºC). Results also showed that air movement improved perceived air quality, and that cooling devices were more effective at improving comfort than heating devices. There was little difference between fixed settings and when subjects had control of the settings, likely because the researchers were able to identify appropriate settings. The study concluded that such devices, in combination with expanded temperature ranges, building HVAC energy could be reduced by up to 40% while providing acceptable comfort (Zhang et al. 2010).

Phase Two: Field Studies with Medium-Fidelity Combined Footwarmer / Fan PCS Devices

The results from the first-generation prototype studies were very promising and led to further studies with more advanced versions of several PCS devices. The second round of prototype development focused on two devices comprised of physical prototypes integrated with electronic controls and data collection systems. This approach of combining physical and virtual elements is described as 'mixed prototyping' by Camburn et al. (2017) which are usually created at 'later stages of prototyping once subsystem prototypes are integrated,' as in this case

The second-generation prototypes consisted of an advanced version of the footwarmer devices, and also IoT-connected desk fans, again based on the concept that head cooling and warming of extremities are the most efficient methods of providing individualized thermal control and comfort. Both devices were prototyped extensively as part of a funded field study (Bauman et al. 2013) and a Master of Science in Architecture thesis (Fannon 2015). In the context of prototyping theory, this work served multiple roles including exploration, active learning, refinement, and in the final iteration as examples of 'research architypes.'

Footwarmer prototyping. The development of the footwarmer prototypes was guided by several goals. One was to make devices significantly more energy efficient than the phase one, 125-watt prototypes. The design team considered various strategies such as radiant panels, ceramic heaters and conductive floor pads, but ultimately decided to keep the basic concept of a footwarmer box with heat lamps. This design is efficient as it focuses heat on the top (less insulated) area of the feet, and it is fast acting through the combined action of radiation and convection confined within an insulated box (Fannon 2015). An early iteration was based on arrangements for lamps that would reduce the amount of unnecessary space within the boxes

(Figure 2) and this led to exploration of a half-ellipse shape form created from curved aluminum and expanding foam, with a foam bumper on the front edge (Figures 3a-c).

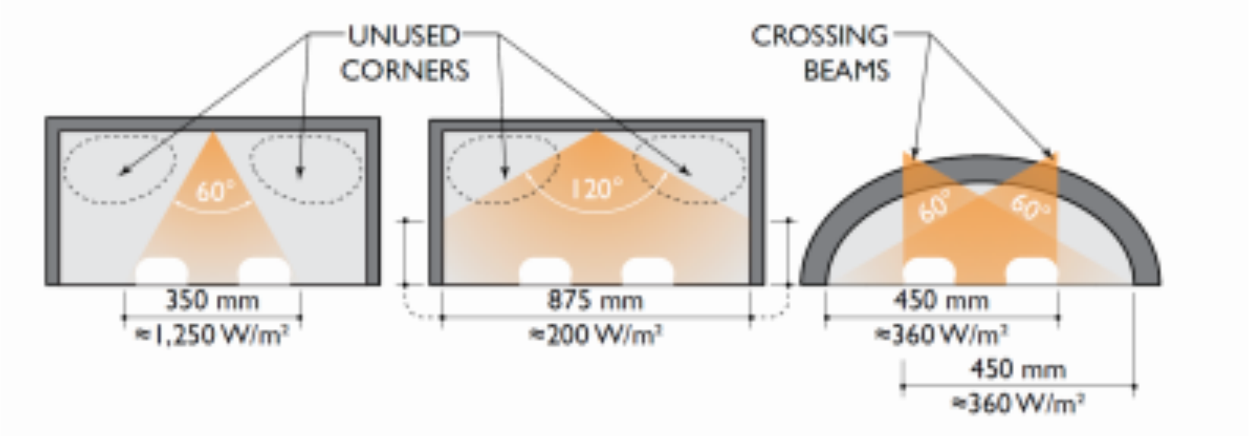


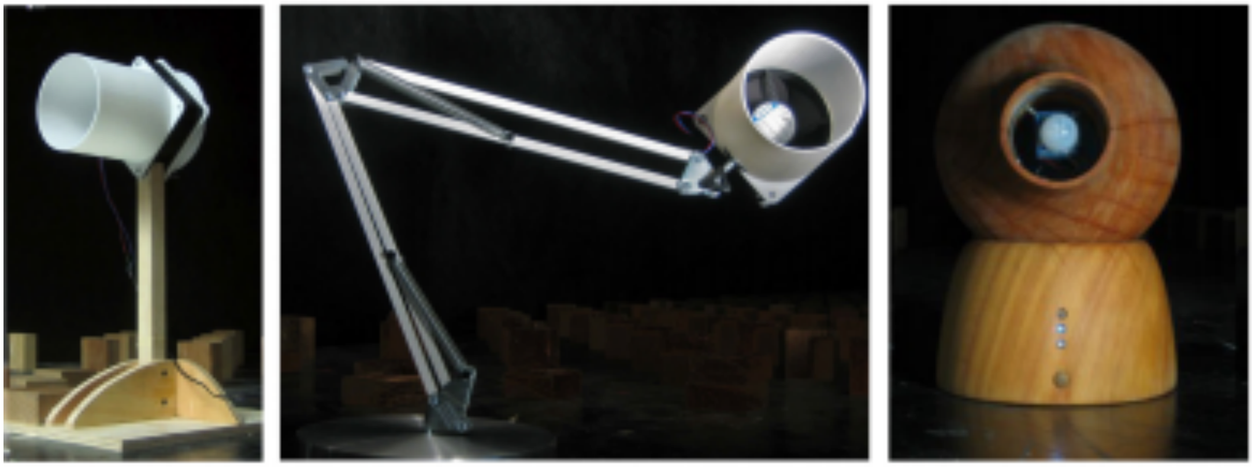
Figure 2. Hypothetical lamp arrangements were studied to reduce unused space and improve radiation heating led to the first prototype design concepts. *Source:* Fannon 2015.

Figures 3a-c. Early prototype for half-ellipse footwarmer, in fabrication and in use. *Source:* Fannon 2015.

Although this prototype sufficiently served the necessary functions, and may have been highly energy efficient, in order to produce the footwarmer in a sufficient quantity a more efficient fabrication method was needed. The team decided to design boxes that could be fabricated by a local sheet metal fabricator. Cardboard models were developed and refined to determine the final design, then measured drawings were produced and issued for pricing and fabrication (Figures 4a-c). The final high-fidelity prototype design included a tread plate that acted as a switch to turn on the lamps, which in turn was connected to a timer that would keep the lamps on for a designated time (to reduce potential distraction from frequent on/off cycling) and to a control dial built into the desk fan, which is described below. The final design, of which approximately 100 were built, required less than 20 watts to provide a whole-body heating effect of 9ºF (5ºC) under steady-state conditions, an enormous energy reduction when compared to the standard commercial portable heaters drawing 750-1500 watts (Bauman et al. 2013, Taub et al. 2015).

Figures 4a-c. Final footwarmer prototype with cardboard mockup, sheet metal layout, and fabrication shop. *Source:* Fannon 2015.

Fan prototyping. For the development of a smart desk fan to provide head cooling, several concepts were tested in parallel, a strategy that led to diverse solutions, and provided the design team confidence in the final solutions, consistent with findings of Dow et al. (2010). The fan was envisioned as the centerpiece of this phase of the PCS, and would also house the user controls and the data collection electronics. The first concept by Fannon (2015) was conceived as a desktop device consisting of a formed plastic base, flexible gooseneck stem, and a fan housing. Fannon's development via a parallel prototyping process created a 'family tree' of low- and medium-fidelity studies. These included articulated 'frankenfan' versions, some built with adjustable lamp bases, used for rapid iteration in order to optimize the nozzle design. A "Woody' version fabricated on a wood lathe was explored to offer a more tactile and user-friendly expression (Figures 5a-c).



Figures 5a-c. From the 'family tree' of fan prototypes, articulated fan, lamp base 'frankenfan' and turned wood version. *Source:* Fannon 2015.

Several frankenfan versions were iterated and tested for cooling performance. Tests included centerline air velocity measurements with various cowling inlet and outlet designs, energy use measurements, and air velocity profile mapping. The results led to improved designs that increased both the fan air range and velocity (Fannon 2015). A thermal manikin was used for a series of tests of the fans' cooling efficiency (Figure 6b). These tests included several commercial fans, and showed that the compact CBE prototypes, while providing only modest whole-body cooling, had energy consumption that was an order of magnitude lower than that of commercial fans (Fannon 2015). The final concept was ultimately similar to the initial concept having a plastic molded base and cowling, connected with a flexible gooseneck, as shown in Figures 6a and 6c. During refinement, several compact fans were tested, and a compact computer fan was selected for both its performance and quiet operation.

Figures 6a-c. Various fan prototypes, cooling performance test with thermal manikin, and the integrated footwarmer and fan installed in a field study site.

As the centerpiece of the system, the fan had many requirements that were refined through an iterative mixed-prototyping process, using SolidWorks software and 3D printing. Working with a manufacturing partner led to the creation of molds and for injection-molded parts used to fabricate the high-fidelity prototypes in larger quantities. The electronics were housed in the base, with two dials linked to LED indicators for activating the footwarmer and controlling the fan speed. An internal metal ballast was added for stability. The onboard research sensor system, built on the Arduino microprocessor platform, enabled the monitoring of occupancy in front of the fan, fan use and settings, footwarmer use, and the ambient room air temperature. The final fan prototyping process included calibration of sensors and repeated testing of the sensor and communication systems to ensure reliable performance during field study durations of six months or more.

Field study implementation and results. The fan and footwarmer PCSs were deployed in several field study sites. The fans were connected through the USB ports of the test subjects' desktop computers, and data was sent using an encoded protocol to protect the confidentiality of subject test data. A winter season study was conducted in an office building with 16 occupants over a six-month period in which temperatures were varied from a baseline condition of 70ºF (21ºC) through three lower temperatures as low as 66ºF (19ºC). During this period data was collected through the PCSs, with plug load monitors for energy use, and using online occupant questionnaires with thermal comfort and air quality questions. The results show that occupants with the footwarmers experienced thermal comfort similar to the baseline condition, even at the lower temperatures. The findings suggest significant energy saving potential from such devices, which used only 20 watts on average to offset 4ºF (2ºC) of room air reduction, which translates to approximately 500-700 watts per person (Zhang et al. 2015).

Phase Three: Prototyping Comfort with Heated and Cooled Office Chairs

The final PCS prototypes developed and tested at UC Berkeley were a series of 'active' office chairs that let users control heating and cooling in the seat and back. An early test of this concept came from tests in a controlled environmental chamber with 16 participants, using a commercial product with thermo-eclectic arrays incorporated into the seat and back. The devices were shown to provide acceptable comfort over a wide range of temperatures from 61°F to 84°F (16°C to 29°C) (Pasut 2013). While these particular devices were not commercially successful and were eventually discontinued, the results suggested that such chairs held promise as PCS devices.

As chairs are ubiquitous in offices, they would seem to offer advantages for adoption over the footwarmer-fan system. Encouraged by the lab results, the research team at CBE embarked on a multi-year effort to develop, refine and test advanced PCS chairs with integral heating and cooling in the seat and back, controllable by chair users, and powered by an onboard battery that would provide several days of regular use. The prototypes were created by modifying standard mesh office chairs that are widely available at many price points. While the prototypes varied, they all contained key elements determined through extensive iteration and testing to be effective. These included reflective surfaces to form plenums at the seat and back, resistive heating strips affixed behind the mesh fabric, small fans in the seat and back, and user controls (Figures 7a-c).

Figures 7a-c. Early heated/cooled chair prototype, fabrication of final design for field research, and thermal camera image with heating elements activated.

The first set of chair prototypes were used in human subject tests that also included small desk fans, producing results similar to the earlier study with the thermo-electric chairs. These CBE active chairs required at most 16 watts for heating and 3.6 watts for cooling. Results showed that the chairs provided comfort from 64°F to 84°F (18°C to 29°C). The tests also showed that the open mesh was not important for the performance of the chairs, as they worked as well when covered with fabric (Pasut 2015).

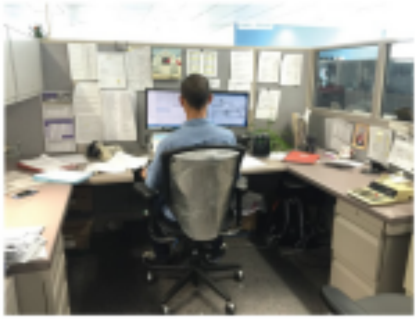
The next step in advancing the chair prototypes was to add sensing and communication capabilities to enable data collection in field studies, similar to the approach used in the fan and footwarmer devices described above, however using wireless communication for data collection. The sensors included chair occupancy, seat and back chair settings, and ambient temperature. These medium-fidelity prototypes included occupancy sensing to reduce battery use, and are described in Bauman et al. (2013, 66-71). The user controls were also advanced through multiple iterations and tests, with a final version that allowed users to control the seat and back independently, a refinement that led to interesting research findings (Figures 8a-c).

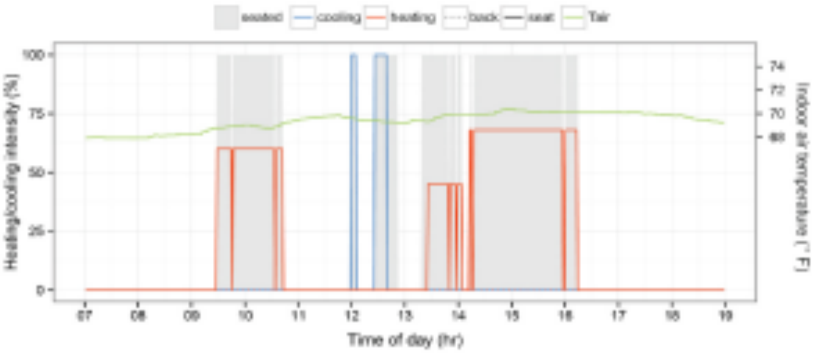
Figures 8a-c. Evolution of user controls evolved from: (left) simple mockup with a knob in the armrest and heating/ cooling toggle; (middle) intermediate version with toggle and dial with binary LED indicators; and (right) the final version with separate controls for back and seat, with 9-point LED indicators.

Six-month field study and results. The chairs were evaluated in numerous study sites in Northern California, in some cases in combination with other PCS devices such as desk fans, footwarmers, and 'legwarmers' — a series of low-fidelity prototypes similar to footwarmers but extending up to occupants' knees. The sites included several UC Berkeley campus buildings, two office buildings with high-performance systems, and most significantly, the offices of San Mateo County where a six-month field study was conducted with chairs given to 37 study participants. At this site the researchers collected over 5-million data points at 20-second intervals, and also 4500 occupant survey responses (Kim et al. 2019).

Results were consistent with earlier studies and highly robust. Participants with chairs reported 96% thermal acceptability, far exceeding the 80% ASHRAE standard that is rarely met in practice. The results showed 99% user satisfaction with the chairs, and that heating or cooling were used 76% of the time the chairs were in use. Surprisingly, the study showed that back heating was used by some participants for therapeutic reasons in addition to thermal ones, and that use patterns varied considerably between participants (Figures 9ab). Anecdotal feedback from study participants was positive, and many asked to keep the chairs after the conclusion of the study.

With this extensive trove of behavioral, subjective and measured data, this work formed the basis for a PhD dissertation showing that 'personal comfort models' based on data from individuals produced superior accuracy than conventional models such as the predicted mean vote (Kim 2018). The work also suggests a 'synergistic effect between PCS and personal comfort models' that could lead to occupants-in-the-loop building controls. While not realized in this study, a final goal of the research team is to use user behavior feedback from PCS devices as input to HVAC system control.





Figures 9a-b. Typical PCS chair user in San Mateo field study, sample chair data from participant over a day. Note that use of seat heating and cooling does not follow ambient temperature trend. *Source:* Kim et al. 2019.

The promising results from these studies, in particular the chair concept, led the research team to pursue commercialization activities, including obtaining patents for the PCS chair (Arens et al. 2017). A commercial license was granted and a product was marketed as the 'Hyperchair' for several years. One noteworthy sale was for approximately 70 Hyperchairs to the Rocky Mountain Institute for their ZNE office building completed in 2015. While the initial intent was to lower the thermostat setpoints for energy savings, RMI determined that the chairs may best be used to address people who are likely to be uncomfortable within the standard range of temperatures (Adams 2016). Feedback from potential customers was that the high-fidelity chair prototypes, and even the Hyperchair design, will require further refinement to satisfy the requirements of typical corporate office designers and specifiers. Bridging the gap to commercial success is a challenge, as 'relatively little research exists on product-service system prototyping and the transition to market, which are successful for transition to commercialization' (Camburn et al. 2017).

Conclusions

A series of prototyping activities spanning several years supported the development and demonstration of innovative ways to provide energy-efficient, individualized thermal comfort using 'personal comfort systems.' The process included serial and parallel development, using both physical and digital methods leading to high-fidelity 'mixed prototypes' that were produced in significant quantities for use in field study research. The prototypes played several roles per Camburn et al. (2017) including design refinement, exploration, and active learning. The work included 'evolutionary prototyping' in contrast to 'throwaway iteration,' as the versions of chair prototypes were continually used in research, even as new ones were created. The prototypes also served as 'instruments of inquiry' and 'research architypes,' per Wensveen and Matthews (2014)

UC Berkeley's research on PCS devices has been extensively documented in reports and papers, and recently led to improvements in the industry guidance provided by the "ANSI/ ASHRAE Standard 55: Thermal Environmental Conditions for Human Occupancy." The 2020 revision will include five-levels of 'comfort control classification.' The level of control is based on the number of thermal control options made available to individual occupants (Arens et al. 2020). Without the highly developed prototypes created by the researchers, it would not have been possible to advance this type of quantitative change to a key industry standard.

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