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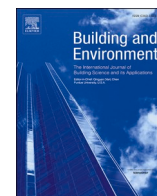
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Usability of personalized thermal control systems by people with intellectual disabilities in energy poverty

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ABSTRACT

This study assessed the usability of three readily available Personalized Thermal Control Systems (PECS)—an electric blanket, a small personal fan, and a large pedestal fan—among individuals with intellectual disabilities living independently in energy poverty conditions in Chile. The research aimed to identify the primary usability challenges that affect the adoption and operational effectiveness of these technologies and, consequently, their potential to enhance thermal comfort. Results indicated that devices with more advanced control features, i.e. the large pedestal fan, presented the most significant usability challenges, followed by the electric blanket and the small personal fan. Key usability issues included poor visibility, inadequate material choice, ineffective communication, bad affordance, and inadequate levels of touch sensitivity of the control interface in these PECS. The study also showed a large variance in the level of adoption of the PECS among participants, thereby indicating that users have different individual attitudes, ranging from passive acceptance to proactive exploration and use. To conclude, this study advocates for the necessity of developing easily operable PECS that cater to the specific needs of individuals with intellectual disabilities, thereby supporting their autonomy and improving their quality of life in thermally comfortable environments.

1. Introduction

Personal Environmental Control Systems (PECS) allow occupants to control their immediate environment according to their personal preferences. Concerning thermal comfort, previous studies have shown that PECS can improve occupant satisfaction and productivity [1–3], whilst having potential benefits in terms of energy performance [4,6] [;]. A large variety of PECS solutions exist in the market, from highly complex and smart systems such as smart chairs [7,8] to more simple low-tech solutions such as hot water bottles or warm-barrels [9]. Regardless of their level of complexity, thermal PECS heat or cool a person by leveraging on conductive, radiant, or convective thermal transfer strategies [10].

Research on thermal PECS focuses on both reducing energy consumption and enhancing environmental satisfaction by providing localized and personalized heating solutions. Recent studies also highlight the benefits of PECS for households in energy or fuel poverty, where a small ventilation fan can be a cost-effective method to mitigate indoor overheating and prevent heat stress [11]. Thus, PECS can play a

central role in thermal adaptation strategies for homes affected by energy poverty, particularly in South America and other developing regions [12,13].

While most thermal comfort research has traditionally centered on controlled office environments [3,14–16], through PECS oriented for computer work contexts [4,5], there is a noticeable gap in studies exploring the impact of PECS on diverse user groups, especially in residential settings. Notably, limited research exists on the use of PECS among people with intellectual disabilities (ID), a group that often encounters additional challenges due to usability issues with interfaces that may be too small or non-intuitive [17,18,67].

Usability is critical, particularly for individuals with ID and the elderly, who may have diminished thermoregulatory responses and a varied perception of temperatures [19]. Effective usability should enhance user satisfaction, accessibility, and the competitive edge of technologies in the market [20]. Usability is defined by Nielsen as the combination of different factors, namely ease of learning, efficiency, memorability, error management, and user satisfaction [21]. The ISO 9241-11 defines usability in terms of effectiveness, efficiency, and

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satisfaction [22].

Usability is user-specific and it should consider the needs of a diverse range of users, including those with disabilities. This is crucial from several perspectives, as it expands the potential market for the technology, but also from an ethical and regulatory compliance perspective. The importance of usability in empowering people with ID to participate more fully in society has been emphasized in previous research [23–25], highlighting the following contributions of usability: (i) Personalization and adaptability to the specific needs of each individual, acknowledging human diversity and meeting the requirements of people with different abilities and cognitive needs; (ii) Promotion of autonomy by enabling people with ID to perform tasks more independently, which promotes their autonomy and greater participation in everyday activities; (iii) Inclusion and participation in society by providing means for social inclusion of people with ID, impacting social integration and participation in the community.

Given these premises, usability is a key aspect in PEC performance, given that PECS aim at providing means for personalise the indoor environment thereby increasing user satisfaction. However, usability is often overlooked, even when it comes to regular users. While some approaches aim to design specific technologies for people with disabilities [24], it has also been discussed that the universal design approach, where the same technologies are useable and accessible to all, can be much more inclusive and a non-segregating perspective. This is because designs that are well-suited to address specific challenges faced by users with disabilities are still acceptable and ready for users without ID [26]. In this sense, the universal design approach requires the simultaneous consideration of physical, sensory, and cognitive accessibility. With the increase in the aging population and a growing number of people described as neurodiverse, the need for an inclusive approach to technology is ever more relevant [27,28]. Under this perspective, the goal is to provide spaces well-suited to everyone, regardless of their age, gender, cultural context, or motor, cognitive or sensory abilities. Universal Design proposes that technologies and services should be accessible from their origin, avoiding creating subsequent adaptations or technologies that are only meant to be used by a specific population [29,30]. However, in order to meet Universal Design requirements, knowledge of the user requirements from a large range of participants with different abilities and expectations is required.

In recent years, interest in researching better and healthier environments for everyone has grown [31–33]. In the professional field, the WELL Building Standard™ version 2 incorporates wider recommendations to deliver spaces that enhance human health and well-being. In this case, they consider a significant section for mental health by addressing factors that influence cognitive and emotional well-being, such as providing a connection to nature and restorative spaces, among others [34]. Similarly, the work done by HOK Group showcases several strategies for creating workspaces that are inclusive of neurodiversity, considering a variety of spaces such as quiet areas, movement zones, spaces with white noise, and non-stimulating or, on the contrary, highly stimulating color schemes [35]. While these advances are relevant, they mostly involve working spaces and leave out people with intellectual disabilities as a target group for inclusion. For technologies, even though the definitions and procedures for usability in interactive devices have been expressed and refined as ISO standards for more than two decades [22], the application of the standard on new technology is not mandatory and has had little impact on current design trends. In this line, cognitive accessibility specifically refers to when the information or instruction is easy or intuitive to understand by any person, regardless of their intellectual abilities [36] and it is expected to have a growing presence in standards for buildings and technologies.

In order to bridge the gap in current literature regarding the dearth of research encompassing users with ID and thermal PECS in a residential context, this paper presents the results of a case study on the usability of thermal PECS from users with intellectual disability. In particular, this work aimed at evaluating what barriers hinder the interaction of users

with intellectual disability with thermal PECS and discuss implications for future PECS design from an inclusive perspective.

A field study was carried out to evaluate the usability of three types of commercially available thermal PECS by people with intellectual disabilities in social housing in Chile. The participants were living in an autonomous manner and in a context of energy poverty. This paper focuses on the usability aspects of thermal PECS, while the impact of PECS in mitigating energy poverty and improving thermal comfort is not addressed in this paper. Usability and interaction were assessed by performing interviews and usability tests. Section 2 describes the methodology used to assess user interaction with PECS, while Section 3 and Section 4 describe and discuss the main findings.

2. Methods

2.1. Participants

To conduct the study, a group of adults with moderate or severe intellectual disability (ID) were selected. Ethics approval for the study was granted by the Bioethics and Biosafety Committee of the University of Bío-Bío, in October 2022. A consent form was designed, following the recommendations for inclusive research that suggests adapting to easy-read by breaking the consent into smaller sections, and having visual and conversational support when needed [37,38]. Eight participants from the program “Transition to Independent Living”, led by Coanil Foundation in Chile, were invited to the study, all of whom personally signed the consent and agreed to participate.

Participants were selected according to two criteria: (i) they live independently; (ii) they are in an energy poverty context.

It is important to highlight that living independently for people with ID means they do not require the help of carers in their daily lives, but it does not imply living alone or without any support [39,40]. In this case, the eight participants lived in two identical social-housing semi-detached dwellings (four in each house). As part of the “Transition to Independent Living” program, the participants received daily visits from professional of Coanil Foundation who provide individual and group support in different areas of development, positively promoting independence, autonomy and, in general, fulfillment of people with ID [41,42]. Five were women and three were men. Their ages ranged from 25 to 57 years. A total of seven individuals were diagnosed with severe disability while only one had a moderate intellectual disability, however, six of them were able to maintain permanent employment. Their intellectual disability was verified through the national disability certificate. Table 1 reports information about the characteristics of the participants.

Energy poverty is the situation of a household when it does not have equitable access to high-quality energy services to cover the basic needs of its members [43,44]. The participants of this study live in a context of

Table 1
Demographic characteristics of the participants involved in the study in terms of sex, age, occupation and level of intellectual disability.

Nº	Sex	Age	Occupation	Intellectual disability
1	Female	42	Paid job - Performs cleaning work at a clothing factory	Severe
2	Male	51	Unpaid domestic work	Severe
3	Female	52	Unpaid domestic work	Severe
4	Female	57	Paid job - Performs cleaning work at a school	Severe
5	Male	41	Paid work - Performs cleaning work at a mesh factory	Severe
6	Female	53	Paid work - Performs cleaning work at a school	Severe
7	Female	54	Paid work - Performs cooking and cleaning at a school	Severe
8	Male	25	Paid job - Cinema assistant work	Moderate

energy poverty, supported by three conditions: (1) the low income of the participant group (even though six participants have paid jobs, most do not reach the minimum national salary due to their job arrangement, with lower weekly working hours), (2) the passive dwellings without centralized conditioning, and (3) the group's lack of knowledge about efficient thermal strategies, both passive and active.

The dwellings of this study are located in the Metropolitan Region of Chile, in Colina, a city with the highest levels of national inequality [45] and where the weather is characterized by a Mediterranean warm summer climate (Cfb of Köppen Climate Classification). The temperatures during the winter period of the study ranged from 1.5 to 25.3 °C outdoors and from 10.4 to 26.8 °C indoors; whereas for summer, it ranged from 8.9 to 35.2 °C outdoors and from 18.3 to 36.7 °C indoors.

2.2. Thermal PECS

The choice of technologies was based on products that are available and economically accessible in the national market, some suitable for winter and others for summer (Fig. 1).

The selection of these technologies considered the socioeconomic context of the case study, prioritizing those more likely to offer high effectiveness and relevance for the users. Although the conversation about technology price was not covered in the interviews, the selection of affordable PECS also responded to this need and is considered a relevant aspect of future PECS development for addressing energy poverty. Eventually, one technology for personal heating and two technologies for personal cooling were identified, namely: (i) Electric Blankets (a in Fig. 1): intended for use during winter, providing direct and personalized heat, it provides a heat level control and can be unplugged to allow washing; (ii) Small Personal Fans: designed for use in desks, or on nightstands, for the summer period (b in Fig. 1). Wind orientation can be controlled manually (up and down); (iii) Large Pedestal Fans (c in Fig. 1): standing fan with DC Motor, suitable for ventilation in warm conditions. It has advanced features such as oscillation, ecologic (automatically adjusted air speed that lower intensity intermittently), and night mode, in a touch interface on the bottom of the fan. The specifications of each device can be found in Table 2.

Before the study, some adaptive technologies such as PECS were already implemented to improve thermal comfort in the selected dwelling, as it generally happens in homes that tend to stay outside the comfort zone during winter and summer [46]. In this case, people had one gas heater per house and one small warm air blower in one the

houses for winter. Both houses had a medium size pedestal fan for summer. For the study, all participants received one personal electric blanket and one small personal fan (eight of each). The large pedestal fans were one per house (two in total) and they replaced the previous medium size fans.

2.3. Usability test

For the study, three usability tests were designed aiming to evaluate each technology individually with participants with intellectual disabilities (ID). Each test followed a 3-step structure incorporating recommendations from Ref. [47], shown in Fig. 2. The tests were conducted in Spanish.

All tests began with a brief introduction and were conducted by two researchers. The sessions were recorded in audio format and the user responses were analyzed qualitatively. The following steps were followed.

1. Pre-test questions to measure anticipation: The devices were presented to the users and they were allowed to visually explore them for 2 min before interacting with them. After the visual exploration, a set of questions were asked to verify if individuals could identify the purpose of the PEC technology and how to use it in their daily lives. The evaluation of anticipation is relevant in usability studies to verify how intuitive the technology is for users. The following questions were asked: "What do you think this technology is for?"; "How do you think it can be used?".
2. Usability test tasks: for each device, between 4 and 5 tasks were assigned for participants to complete. The tasks are reported in Table 3. These tasks involved activating essential functions of the devices, such as turning on, changing to a specific heat or air speed level, and turning off. The start and end times of each task were recorded, as well as the task's success. Observations were also made regarding aspects that were confusing, based on in-person observation during the test, considering users' facial expressions, and the exact order of actions or approaches they took to accomplish each task.
3. Post-test questions: the post-test questions aimed to explore projections of the use of each technology as to where and when people would likely use them in their residential context. Examples of questions are: When would you use this technology in your daily life?

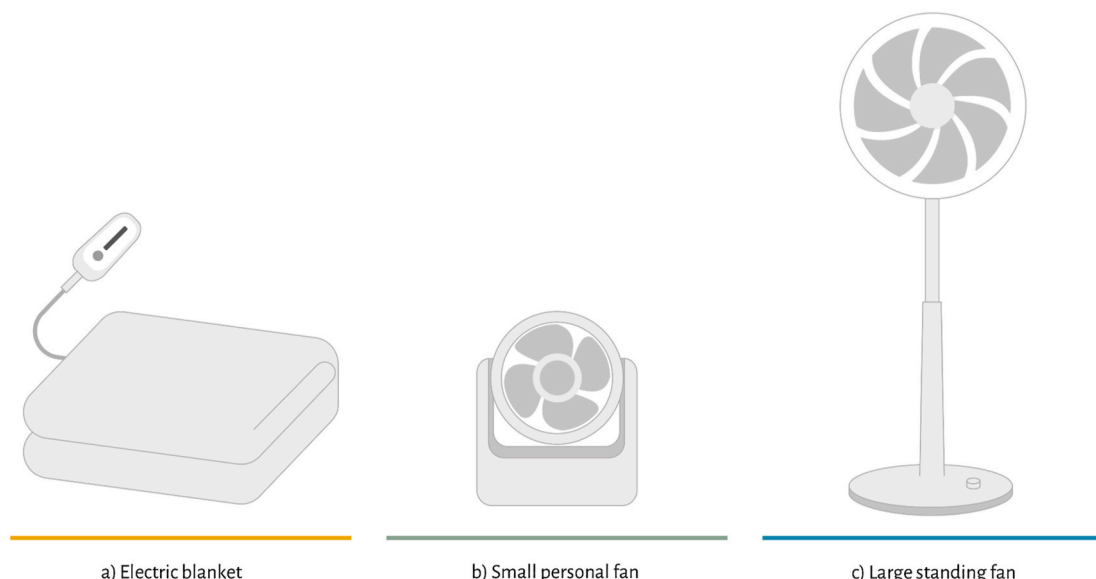
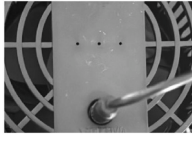


Fig. 1. PECS selected for the research from left to right a) Electric blanket, b) Small personal fan, c) Large pedestal fan.

Table 2
Thermal PECS specifications and interface characteristics for personal control.

Type of PEC	Specifications	Dimension	Personal control	Interface image
a) <i>Electric blanket</i>	- Blanket material: polyester - The blanket can be unplugged to wash 100 kw power	- Width: 130 cms - Length: 170 cms - Full bed size - Weight: 1489 gr	- Selection among three heat levels through one physical button - Visual feedback indicates the heat level through a light that marks from 0 to 4, from yellow to red	
			A plastic plug and clip between the blanket and the cable, allows to unplug	
b) <i>Small personal fan</i>	- BLDC Motor - USB charger - Three air speeds - Detachable grille - Lithium Ion Battery ICR 18650-3.7V 2200 mAh - Up to 45 min of battery autonomy 4 W power	- Width 14.8 cms - Height: 9.8 cms - Depth: 16.8 cms - Weight: 330 gr	A button on the back of the device enable to switch on or off and adjust the air speed	
			Air speed is indicated by a visual feedback from 1-to-3 lights	
c) <i>Large standing fan</i>	- DC Motor 24 air speeds 30 W power - Horizontal oscillation - Low noise 3 modes: Normal, Ecologic, Sleep 7 14 cm blades - Timer: On/Off 8 h	- Hight: 108 cm - Diameter: 41.5 cm	- Switch on/off button - Continuous knob for air speed control - Light visual feedback through air speed number	
			- Touch button panel for advanced features - Light visual feedback for advanced features though pictograms	
			Pedestal physical button to adjust fan height	

Where do you think you could use it at home? These questions were later used to understand users' anticipation towards each PECS.

As shown in Table 4, a quantitative and qualitative analysis was carried out to evaluate the PECS's effectiveness, efficiency, satisfaction, and adoption.

Effectiveness. Effectiveness was measured using a binary task success metric, indicating that every task has a clear goal to be achieved, and participants can succeed or not, with no intermediate nuances.

Efficiency. To complement the task success analysis, efficiency was observed through a task completion time measure.

Satisfaction. Satisfaction was addressed by identifying and describing usability problems using an inductive method, based on the evaluators' observation and audio recordings, where confusion and deviations are observed in the process of performing a task with a technology. These problems are subsequently quantified and categorized by level of severity in each case. Satisfaction is measured in two ways: (i) by counting the frequency of barriers that hinder user interaction with the PECS; (ii) by evaluating the severity of the usability barrier.

The frequency of the error was quantified by identifying the number of people affected by each issue in the usability tests. The frequency is linked to the number of participants in the study, so the highest possible recurrence is 8, and the lowest is 0 (no occurrence).

The severity of each problem was defined using a scale based on the impact on user experience, drawing from the guidelines suggested by usability experts [20,48].

1. Low severity: Users can complete the task with a brief slowdown or confusion, or the finding is primarily cosmetic. This problem reduces to a little extent efficiency or satisfaction.
2. Medium severity: Users were able to complete the task but with observable frustration, noticeable slowing down, or after several attempts. This problem impacts the efficiency and satisfaction of users.
3. High severity: The problem caused users to stop their task or resulted in clear frustration or guilt due to difficulties with the experience. This problem significantly impacts effectiveness, efficiency, and satisfaction.

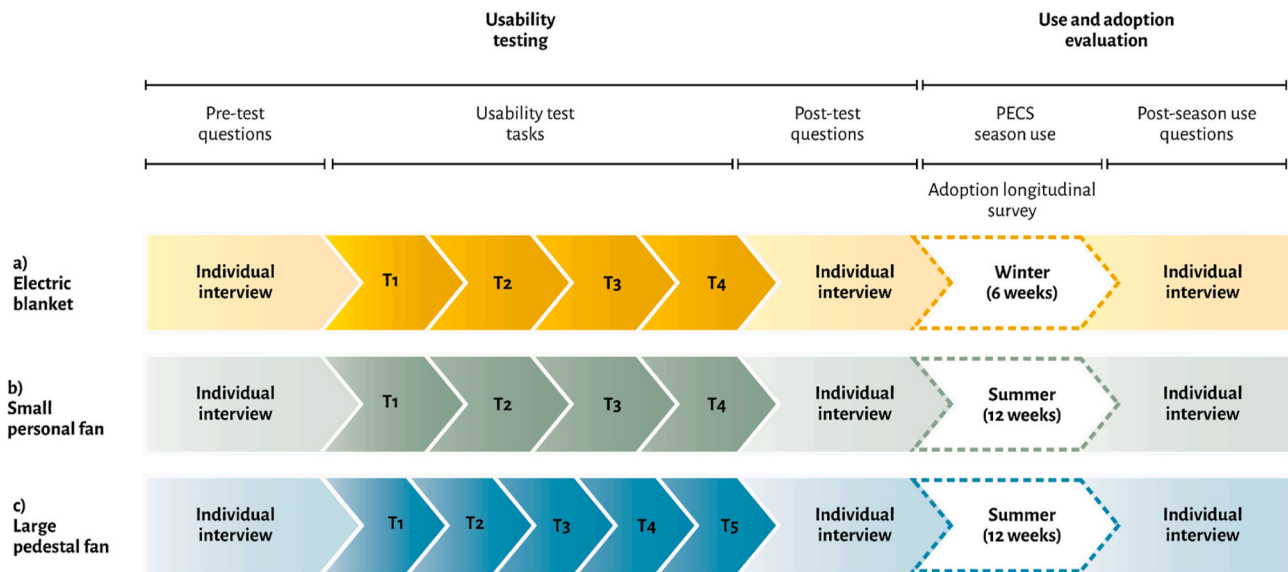


Fig. 2. Test design for 3 selected PECS depicting the steps: Pre-test questions, Usability test tasks, Post-test questions, PECS season use and Post-season use questions.

Table 3

Tasks performed in each usability test with the Electric blanket, Small Personal Fan and Large pedestal fan.

PECS	Task 1	Task 2	Task 3	Task 4	Task 5
a) Electric blanket	Connect plug	Increase heat level to 3	Decrease heat level to 1	Turn off	–
b) Small personal fan	Turn on	Increase air speed to 3	Decrease air speed to 1	Turn off	–
c) Large pedestal fan	Turn on	Increase air speed	Activate oscillation	Decrease air speed	Turn off

Table 4

Methods and metrics used to assess usability of PECS during the field study.

Metric	Anticipation	Effectiveness	Efficiency	Satisfaction	Adoption
Evaluation method	Qualitative assessment through interview	Binary evaluation: 0 - task has been completed 1 - task not completed	Time of completion [s]	1. Identification of barriers to user interaction with PECS 2. Frequency of reported barriers and problems to satisfactory use of the PEC 3. Level of severity of usability barriers	Self-reported usage and interaction by the users Interview with users at the end of each season.
Details	Questions: "What do you think this technology is for?"; "How do you think it can be used?"	Evaluated by the researcher through observations	–	Qualitative assessment through observations and analysis of participants verbalized thoughts. Count of the number of participants affected by the usability barrier. Qualitative assessment of the severity of the barrier according to Ref. [20,48].	Interaction frequency and adoption is reported in daily questionnaires.

Categorizing the severity of usability problems is important to prioritize sensitive aspects that can have a greater impact on the adoption of technologies. This is relevant since some frequent usability problems may not be severe and not negatively impact long-term interaction with technology, as users may overcome the obstacle with relative ease. However, less recurrent usability problems can sometimes be very severe and limit, or outright exclude people by not allowing successful interaction with the technologies. In this study, where the sample size is particularly small, severity can be considered more relevant than frequency.

Adoption. To record and measure user adoption of PECS during the study, a questionnaire was used during the monitoring campaign. Participants were encouraged to answer questionnaires daily and to report the use of PECS when pertinent, through visits from Coanil Foundation professionals. It is worth noting that the professionals reminded the participants to reply to the questionnaire, but it was the people with ID who answered autonomously through personal tablets given to them for

this study. Two months after introducing the technologies during their respective seasons—winter for the electric blanket and summer for the fans—post-season (Fig. 2) semi-structured individual interviews were also conducted to delve deeper into the experience of using these technologies and their adoption. The adoption was analyzed using a mix of quantitative and qualitative methods. The survey allowed to observe to a certain extent the seasonal use of each PECS. Details are also reported in Table 4.

3. Results

3.1. Anticipation of the usability of PECS

Fig. 3 shows how the participants envisioned the use of the PECS in their daily lives by means of word clouds, and as evaluated from the pre-test and post-test questions during the usability test.

For the electric blanket, the key concepts associated with this PECS

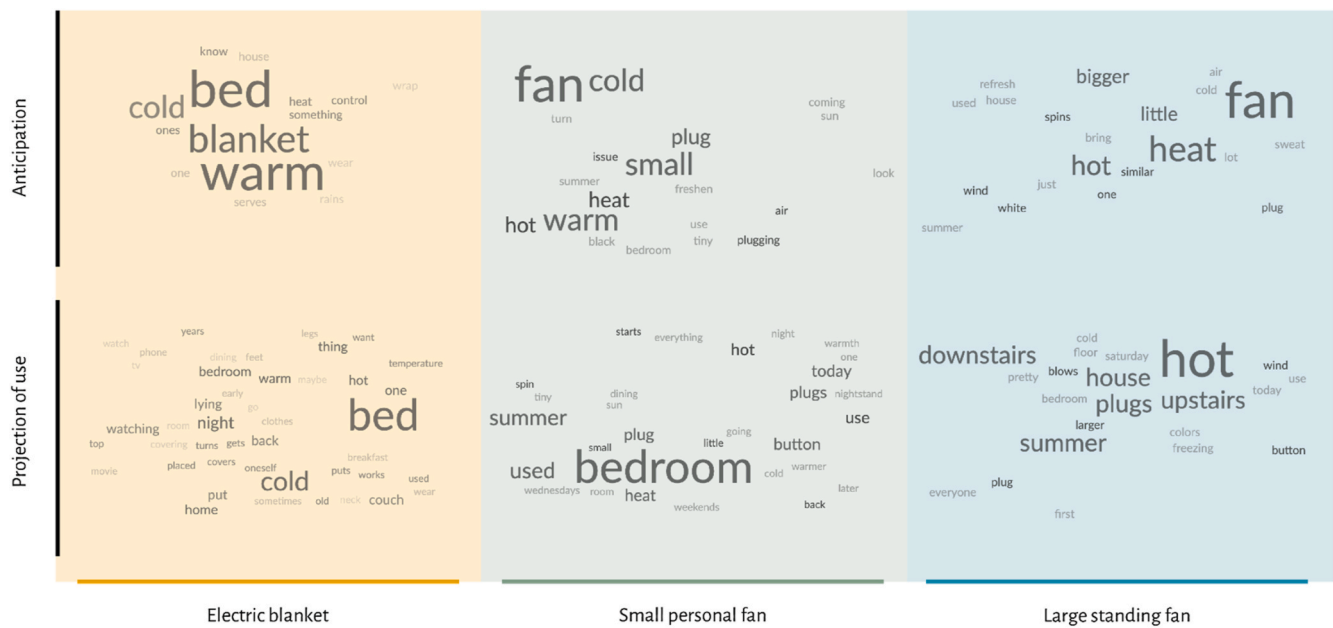


Fig. 3. Word clouds addressing pre-test and post-test questions “What is this technology for” (above), and post-test questions “When or where would you use this technology” (below) for each PECS evaluated. The word clouds were created using <https://www.freewordcloudgenerator.com/>.

were clearly identified by the participants. Words such as warm, bed, and blanket were frequent and present in most answers. The participants primarily related the blanket with the bed and did not explore much further to other possible uses, locations, and actions for this technology.

The small personal fan had a less evident association with feeling hot or with cooling air, as some participants related the device to warm air blowers. Although this fan is significantly smaller than regular warm air

blowers its shape is similar, which appears to have impacted their anticipation towards this device. The main suggested context of use was in the bedroom.

The large pedestal fan was associated with the key concepts of fan, hot, and heat. The shape of this fan felt familiar to the participants so they quickly identified the technology and its purpose. The suggested context of use in the dwellings is broader than the other PECS, as they

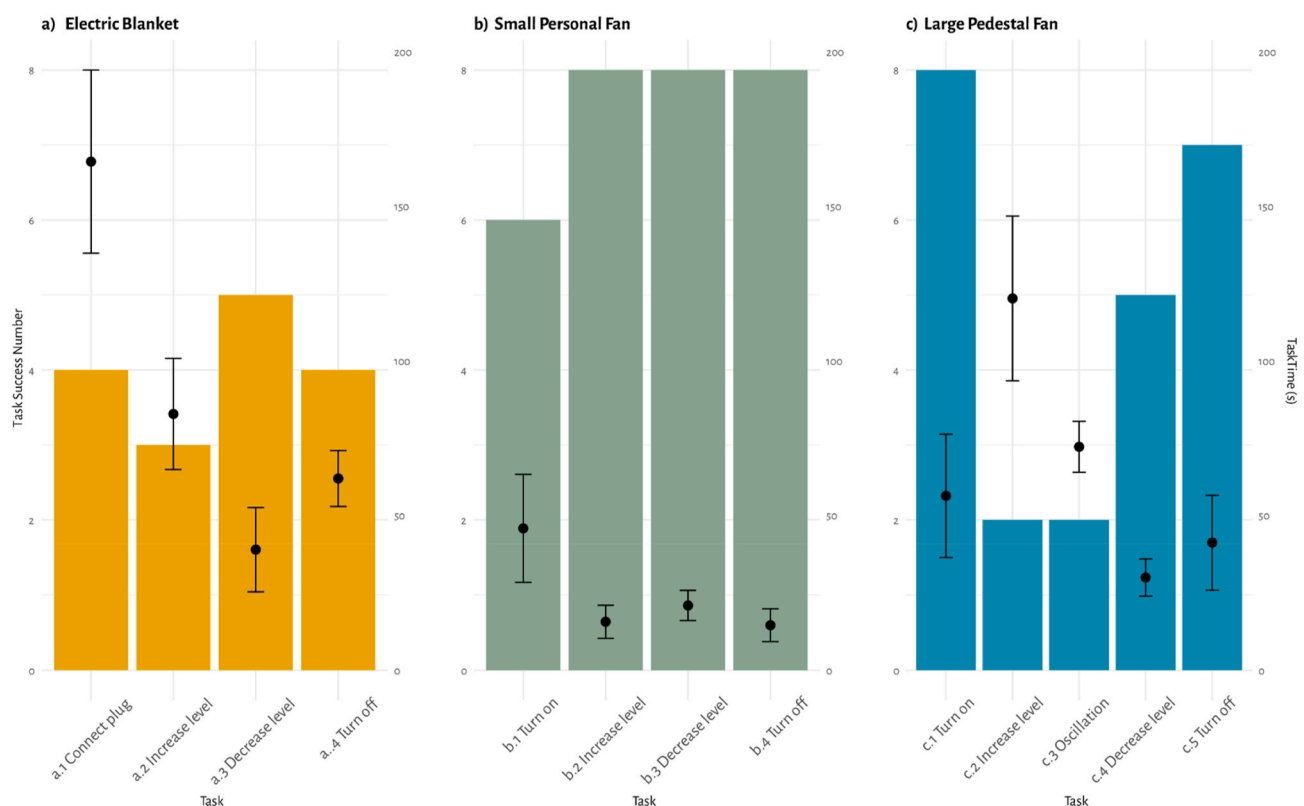


Fig. 4. Effectiveness and efficiency of 3 PECS evaluated. Effectiveness is indicated by task success number (bar plot), and efficiency, by time of completion (error bars). Error bars the mean time and its variance.

imagined using it on the first floor in a shared space and on the second floor, in their bedroom. Most participants also mentioned summer and hot weather as a context of use.

Overall, the users were able to anticipate when and how the proposed thermal PECS could be used.

3.2. Effectiveness and efficiency

Fig. 4 shows the results of the usability tests, presenting the effectiveness of each task through the number of completions or goal achievements, and the efficiency through the average time spent on each task.

The usability test of the electric blanket had a generally low level of achievement per task. Only 4 of the 8 participants managed to connect the electric blanket's cable (task a.1 in Fig. 4), also taking the longest average time from all 3 evaluated technologies (average of 164 s). Notably, the task of increasing the heat level on the blanket to level 3 (task a.2 in Fig. 4) had the lowest success rate, with only 3 people fully achieving the goal. Reducing the heat level to 1, was the task with the highest achievement and was completed by 5 participants, with an average time of less than 50 s. Turning off the electric blanket (task a.4 in Fig. 4) was achieved by 4 participants, taking more than 60 s on average.

The usability test of the small personal fan had a high rate of effectiveness and efficiency for most of its tasks. A total of three out of the four tasks were achieved by all 8 participants and with a low completion time, compared to other usability tests with PECS. Turning on the fan (task b.1) was the only task not achieved by two participants and had a longer dedication time (over 25 s).

The usability test of the pedestal fan showed diverse results depending on the task. This usability test was the only one with five tasks, which included activating the fan's oscillation function (task c.3 in Fig. 4). Turning on the fan (task c.1) was supposedly the easiest task and it was achieved by all participants, however, in a longer time than the other tasks. Increasing the air speed (task c.2) had a low level of effectiveness, where only two people achieved the goal and with a high completion time. This usability test is the only one that considered five tasks, incorporating one associated with activating the fan's oscillation function (task c.3 in Fig. 4), where the result shows a low level of achievement, of only two people. Decreasing the air speed (task c.4 in Fig. 4) was achieved by five people, with the shortest record time in the test (average of 29 s) which could indicate a fast learnability curb in the use of air speed control. Finally, turning off the fan (task c.5 in Fig. 4) was one of the tasks with the highest effectiveness, being achieved by 7 out of 8 participants, however, the achievement time averages 41 s, which is considered a long time for the complexity of the task.

3.3. Satisfaction: usability problems, frequency, and severity

To address satisfaction with the personal systems, usability problems were identified in each technology evaluated. Each problem is described in Table 5.

3.3.1. Frequency and severity of usability problems

Fig. 5 shows the frequency and the severity of the usability problems identified in each device, presenting the frequency through bars that go from 1 to 8 (according to the number of participants that encountered the usability problem), and the severity through a color scale of low (light peach), medium and highly severe (darker red).

There were four usability problems identified concerning the electric blanket, three of which were related to the blanket's connector (a.1, a.2, a.3 in Fig. 5). Specifically, problems such as the connector being difficult to locate and hard to plug were experienced by 5 out of the 8 participants, whereas finding the correct side of the plug appeared as a problem only for 3 users. The reasons for these problems may be due to poor material decisions that cause stiffness in the plug, and the lack of visual

Table 5

Definition of usability problems associated with the PECS electric blanket, small personal fan, large pedestal fan.

PECS	Problem	Description
a) Electric blanket	1. The plug on the blanket side is barely visible.	It is difficult to find the connector entry point on the blanket. The electric blanket is large and there are few visual cues to guide the search. It requires covering the blanket with hands and eyes with great concentration.
	2. The plug on the blanket side is hard to connect	Connecting and disconnecting the cable to the blanket requires physical strength. The blanket can break if strong pressure is applied, but without pressure, it will not disconnect properly. It is a problem associated with the materiality and design of the fitting piece.
	3. The plug on the blanket side only fits on one side	The plug entry piece on the blanket side connects to only one side. However, the piece is symmetrical and looks identical on both sides. The visual indicator for the correct side is subtle and hard to notice due to low contrast (a white indicator on white plastic).
	4. The heat levels visualization on the control is abstract	The control adjusts the heat level using colors ranging from yellow (lowest) to red (highest). The progression of heat levels is abstract and not easily understood by all test participants.
b) Small personal fan	1. The on/off button is not in a central location on the appliance.	The focus of attention is on the front logo of the device and there are no buttons visible from the front face. The most important interaction of on/off and levels is hidden at the back and bottom of the device, so it takes time to find it.
	2. It is difficult to identify the air speed button (same on-off button)	The interaction to modify the air speed is on the back and down button (same on/off button) so it takes time to identify it.
	3. It is difficult to manipulate the air speed button (same on-off button)	By applying more pressure on the main button, the device turns off instead of changing levels. Also when using the same on/off button to change the air speed, it can be pressed more times by mistake and turned on again.
	4. The display of air speed is abstract and inconspicuous	The air speed are displayed on the back of the fan, with dots of light that increase as the air speed increases. However, this visual mark is extremely discrete and the levels are more likely to be recognized by the changes in the air movement and sound.
c) Large pedestal fan	1. The on/off button is not in a central location on the appliance.	Expected places of interaction with the large fan are the pedestal and the back. However, in this artifact, they are located at the base. People confuse the on/off button with the pedestal height adjustment button and even with screws on the appliance, so it takes time to find it.
	2. The on/off button is difficult to control due to sensitivity	The sensitivity of the on/off button is very high, so when pressed stronger the fan turns off and on again. This can happen several times, generating

(continued on next page)

Table 5 (continued)

PECS	Problem	Description
		frustration in people, until they manage to control the touch intensity.
3.	It is difficult to identify the air speed button	The air speed control is physically located in the same place as the on/off button but with different interaction gestures. The on/off button works with pressure on the top, while the air speed control is a knob around the button (click versus twist). This double interaction on the same element is not intuitive or predictable.
4.	It is difficult to manipulate the air speed button	The air speed button/knob rotates continuously, going from the maximum level to the minimum in one small movement., making it difficult to reinforce the perception of the minimum and maximum levels. Also in some cases, the knob is expected to reach zero (such as the small fan), however this does not happen with the pedestal fan.
5.	The pedestal button is too conspicuous on the device.	The height adjustment button on the pedestal is more striking than the on/off button. The button on the pedestal takes center stage and is apparently more “actionable” than the touch buttons on the base as it is a physical button.
6.	The touch buttons are not explicit as an interaction element.	The secondary buttons on the large pedestal fan are displayed with illuminated pictograms on the base of the pedestal. People don't tend to interact with the base of the fan as they don't appear to be actionable buttons, just flat information.
7.	The oscillation pictogram is hard to understand.	The oscillation function is represented by a pictogram of arrows in two directions. The meaning of the oscillation pictogram is not intuitive for the test subjects.
8.	Advanced settings are difficult to understand and to interact with	Advanced settings such as automatic shutdown scheduling are not clear. Furthermore, it is possible to activate them by mistake by accidentally pressing a touch button and causing further confusion, for example, by not being able to turn off the fan if it is in automatic mode. Many times, it is not understood what the functions mean when pressed, because they may not generate an immediate change in the device.

cues to guide the plugging action. Only one additional usability issue was noted, concerning the interaction with the blanket's control (a.4), which works by pressing the same button several times to select from the off state to the highest heat level, in ascending order. However, because the blanket takes time to change temperature, understanding the temperature level relies primarily on the interpretation of abstract visual codes of lights and dots in the control, to infer what it means for the blanket to be more or less warm. 5 out of the 8 participants did not understand the visualization and therefore had difficulties identifying an exact heat level. The four problems were ranked for most cases as highly severe, as they caused frustration and low levels of success per task, especially for the abstraction of the blanket's control.

The small personal fan presented a few usability problems. Generally, participants found it straightforward to interact with the device and to carry out the tasks during the test. Among the 4 identified problems, only one was frequent (locating the power button) impacting five participants, for whom two the problem was ranked as severe (b.1 in Fig. 5). Despite taking longer to locate the button, the participants expressed significant interest in the device, appreciating its ease of use, as with just a single button, they were able to power it on, change air speed, and turn it off. The problems for finding and interacting with the air speed control and not understanding the air speed visualization were ranked with low severity, as most participants could finish the tasks and overcame the usability problems with little observable frustration.

The large pedestal fan presented the most significant usability challenges, with a total of 8 identified problems of varying frequency levels and severity. Notably, 2 problems impacted all participants: The problem to identify the air speed button (c.2) and the problem to understand the oscillation pictogram and button (c.7). Both problems were also ranked as highly severe as they resulted in longer times per task, visual and verbal frustration, and low levels of task success. The next most frequent problems related to not being able to find the power button (c.1) and not understanding the touch interaction of the secondary buttons (advanced settings, c.3 in Fig. 5). In general, the interaction through a button (on/off) that is also a knob (air intensity levels) was confusing and difficult to intuitively understand by the participants. Also, the secondary functionalities of the fan, which are accessed through touch buttons on the bottom of the fan, were not understandable to most people. This is consistent with findings that mention that for people with intellectual disabilities, buttons or actuators must be explicit both physically and visually [49], something that does not occur with touch interfaces, which generally have a smooth or glazed surface.

3.4. PECS adoption

The survey had a total of 330 responses over the winter (42 days) and 577 responses over the summer (84 days). The participants were encouraged to answer the questionnaires, if they were at home and by selecting the PECS that were in use at that point in time. The survey results (Fig. 6) show a low frequency of use of the electric blanket during winter, with 4 % of answers acknowledging its use, with a homogenous distribution of use along the day, from 8:00 to 20:00 h. During summer, however, both fans had high rates of use. The small personal fan had 9 % of use spread mostly during morning and evenings, and the Large pedestal fan showed wider everyday use (34 %), especially in the evenings between 16:00 and 21:00 h.

The semi-structured individual interviews conducted after the winter season, allowed to gather deeper insights regarding the adoption and use of electric blankets by the participants. It was noted that both mornings and nights indoors during the winter were described as cold by most interviewees, leading to the adoption of various personal strategies to adjust. The adaptations ranged from adjustments in clothing, such as wearing multiple layers and warmer garments, to using gas and electric heaters, increasing the consumption of hot beverages like tea and coffee, and using the electric blanket.

Out of eight participants, six reported using the electric blanket during winter in the interviews. Four mentioned using it frequently, highlighting the immediate heating and comfort it provides as the main benefits. Two participants declared not using the electric blanket during winter, citing forgetfulness at the moment of feeling cold and the lack of available power outlets in the bedrooms as the main barriers to its use. Despite expressing interest in the blanket, these individuals did not get accustomed to incorporating the technology into their winter routine. It is worth noting that the electric blanket presented three usability problems related to the plug (Fig. 5 a), which may have affected the participant's interest in operating it at the beginning. The interviews allowed to understand that the participants who used the blanket the most did not unplug it often “I use the blanket at night. When I feel cold I

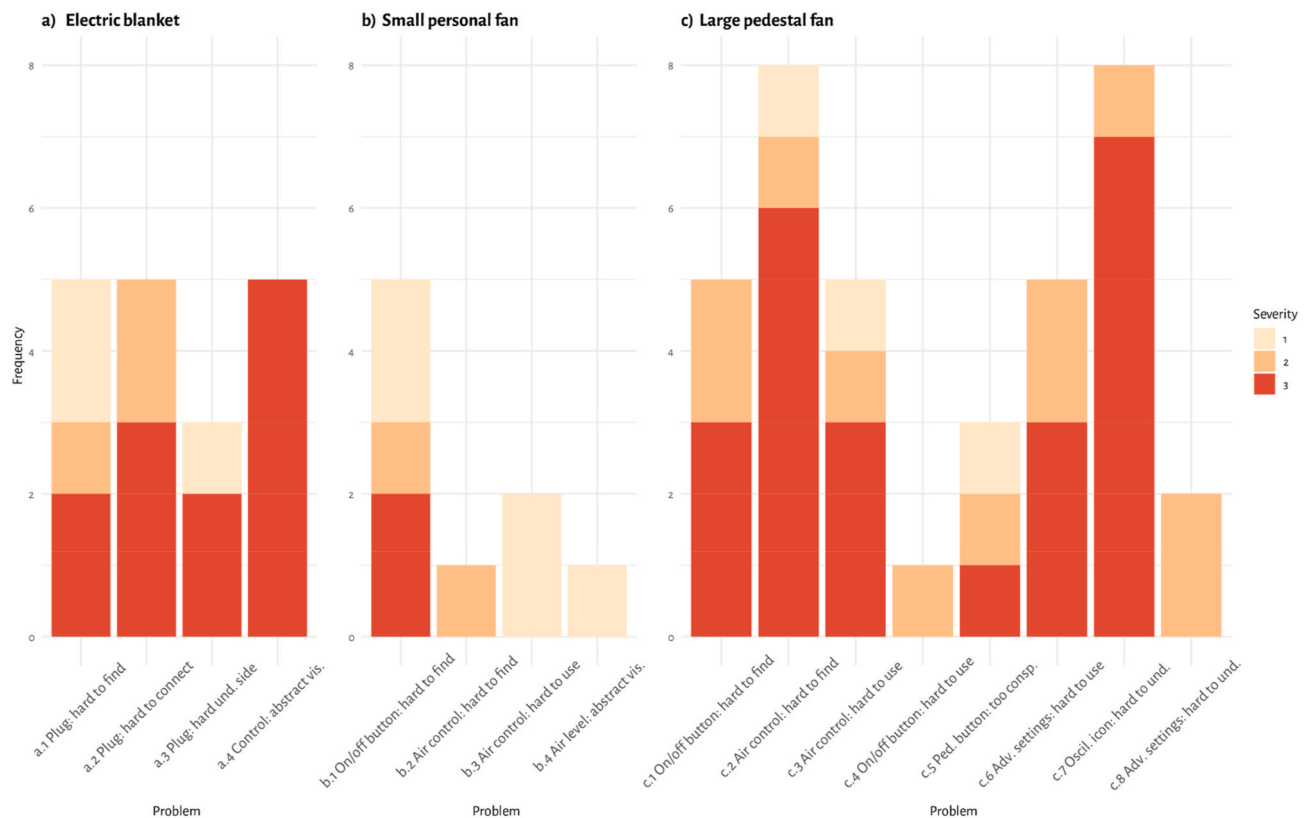


Fig. 5. Usability problems identified for each PECS, presenting the frequency (1–8) and the severity (scale 1 to 3, from low to high severity).

turn it on right there, only when I'm lying down". The use of the electric blanket was reported almost exclusively on beds and during the night, with only one person mentioning its use in the mornings and another on the sofa on one occasion. This can explain the results on Fig. 6 c which show little use of the blanket while answering the survey, as most answers were done during daytime and the blanket was mostly used during night time. The use was primarily individual, except for one participant who acknowledged sharing the blanket with another person a few times.

On the other hand, the interviews conducted after the summer gathered perceptions on the adoption and use of the small personal fan and the large pedestal fan. It was observed that, although three people mentioned feeling warm in the mornings during summer in their homes, three expressed well-being or neutrality regarding the fresher temperature at that time. At night, six participants experienced a lot of heat, noting that it only cooled down in the early morning, and three of them often opted to sleep without covers due to the heat.

Personal strategies to adapt to the warm temperatures included wearing light clothing, such as shorts, dresses, and short-sleeved shirts, and other actions like showering more frequently, keeping their hair wet, cooling off with a hose, and increasing the consumption of water, juice, soda and ice cream. Opening windows at night and doors in the morning also allowed fresh air in. Four people explicitly mentioned the use of fans as an important strategy to cope with high indoor temperatures.

When asked specifically about the use of fans, all participants reported using the small personal fan during the summer, which matches the results shown in Fig. 6 b, although two of them used it only sporadically. The ease of use and effectiveness in air circulation were highly valued aspects, highlighting their autonomy in operating the device with comments like "I learned how to use it" and "It's not hard for me to turn it on". The primary use of the small fan was in the evenings in their bedrooms, located on the second floor, where some participants shared it or used two simultaneously in the same room. Its use on the

first floor was also mentioned while staying on the sofa or watching television, especially in the afternoons after work and on weekends. One person mentions the portability of the small fan as an added value.

Regarding the large pedestal fan, despite being the technology that presented more issues that were more frequent and more severe for the participants (Fig. 5 c), seven people indicated they had used it during the summer, where one specially highlighted its advanced features "I was surprised because I had never seen such a modern fan, with touch and digital buttons". However, four participants faced difficulties in turning it on and adjusting its functions autonomously, citing usability problems "I know where the big button is, but I don't know how to turn it on", "It's hard for me to use it.". Despite these issues, most users valued the fan's air power to combat the heat, as in both homes, certain individuals took on the responsibility of operating the fan at specific times, benefiting those who did not know how to use it or had problems trying. One person mentioned not liking the fan at all, and another, mentioned feeling insecure about mistakenly changing the settings of the fan if they use it. The main use of the large fan was during the day and evenings after work, which matches the results in Fig. 6 c. The large pedestal fan was mostly used in shared spaces on the first floor, especially during activities such as cooking, dining, or watching television. During the summer vacation weeks, the pedestal fan was used more intensively as people spent more hours in their homes. The survey responses support that the large pedestal fan had a significantly higher rate of use in relation to the other PECS (Fig. 6 b). However, it is arguable that even though this system was used more, many people could not operate it independently and they were only passive users, therefore, the shared living condition had a positive impact on the adoption of the large pedestal fan, which was found to have the most usability problems. This is interesting and could be further studied by characterizing the thermal personalities of people with ID, as Bennet et al. did using a personas-based approach for the elderly population [50].

Although the ID level was not specifically compared in this study due to the small sample size and the lack of uniform data, it was possible to

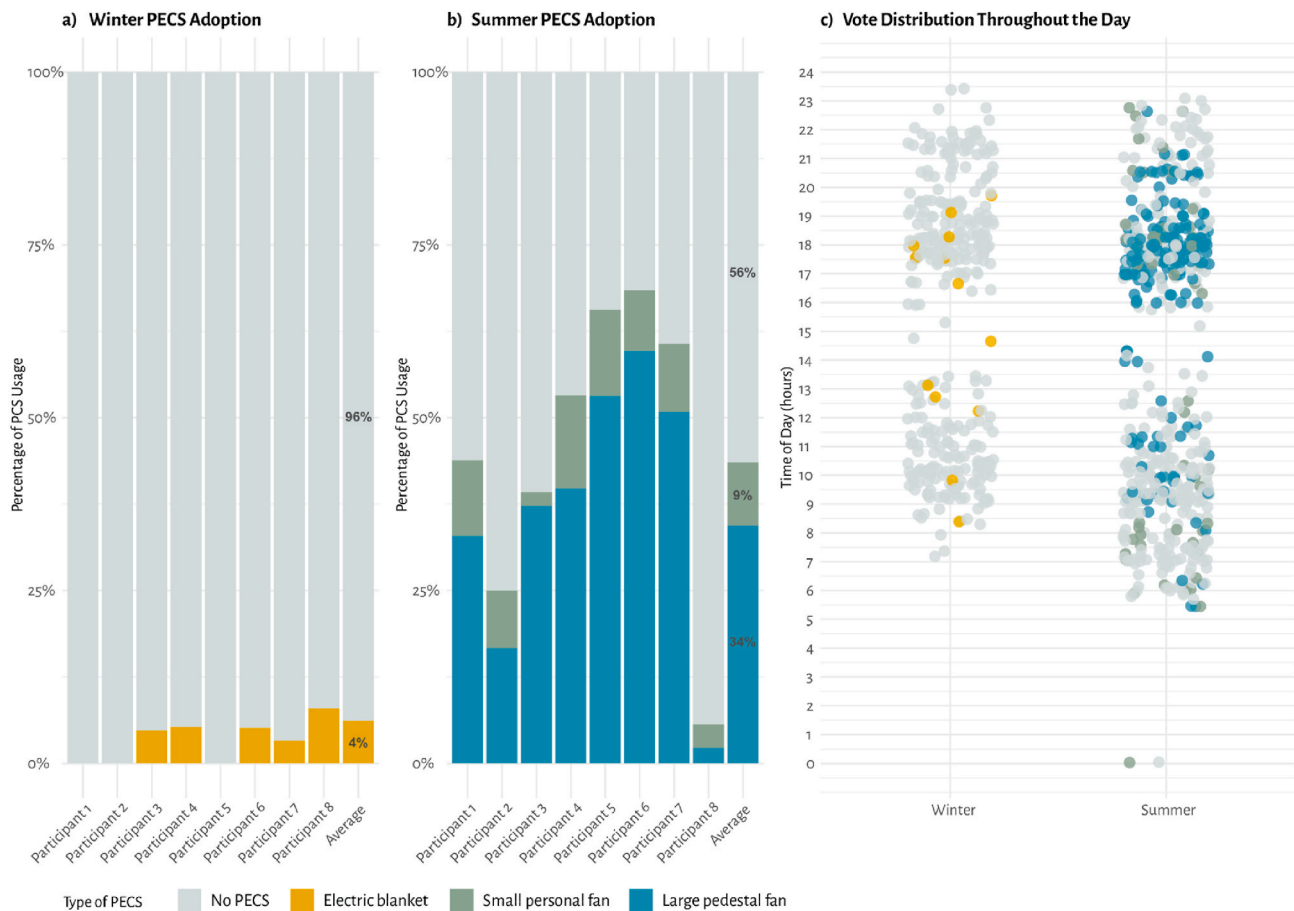


Fig. 6. This figure shows the use of PECS by participants based on survey responses during a) winter, a) summer, and c) the use of PECS throughout the day showing the hour distribution of votes.

observe that the participant with moderate ID (one) experienced fewer usability problems and those of lower severity when interacting with the devices, compared to the others (seven). This also meant that this participant had shorter completion times and higher task success rates. Among the participants with severe ID, there was a wide variety of results from one person to another and even within the same individual. This suggests that the results in people with more severe ID levels may be less consistent, but this requires further research with this particular audience.

4. Discussion

As people with ID transition towards independent ways of living, diverse thermal strategies will be needed to improve their health and well-being indoors, especially in contexts of energy poverty [51,52]. The design of thermal systems and related PECS affects their autonomy and their ability to self-regulate in their homes. From this field campaign, five key learnings are identified as relevant for PECS interaction design considering a wider audience of people with ID: clear visibility, material choice, communication effectiveness, affordance and touch sensitivity. Each one will be developed in the discussion.

4.1. Visibility

Have clear hierarchies for the most critical interactions (such as on/off and heat/air control). Follow device conventions and avoid extreme minimalism that might obscure essential functions.

The usability tests run on the electric blanket, small personal fan and large pedestal fan, revealed several usability problems that impacted the

use and, sometimes, the adoption of these PECS. In some cases, critical interactions such as turning on and off a device, or activating the heating or cooling features, had little visibility impacting the experience of use of the selected PECS. For instance, the small personal fan had a discrete and flat on/off button on the back of the device, and the large pedestal fan had touch buttons that were less visible compared to physical and more robust buttons. This aligns with the idea that both interaction and information need to be prioritized in clear hierarchies in order to be easier to understand by everyone, as established in the field of user experience [53] and in research about people with ID and technologies [49,54].

4.2. Materials

Select materials that are soft and comfortable to touch, ensuring that users can interact with the device without needing to exert significant physical force or possess advanced motor skills.

The choice of materials created usability barriers for the electric blanket, specifically in the clip that allowed the cable to be unplugged from the blanket. This PECS employed a hard plastic clip, which required physical strength and fine motor skills to operate, and only four out of the eight participants were able to manage it successfully. Many individuals with intellectual disabilities (ID) also contend with additional motor impairments [55], which makes it difficult for them to press, control, grasp, or hold accurately. Previous research has shown that although some people with ID can understand the task they need to perform, they are unable to operate the interface properly due to motor limitations with their hands [56]. Material choices can lead to the creation of hard buttons or joysticks that require physical strength or high

levels of fine motor skills, which should be avoided.

4.3. Communication

Minimize the use of visual abstractions to prevent confusion. The device should provide immediate and clear feedback once a setting is activated. Consider auditory feedback in addition to visual.

Communication relates to how technology gives permanent and clear guides and feedback to users and it is acknowledged as an important principle for interaction design [57]. This was achieved in the selected PCS by the use of pictograms (as in the large pedestal fan), color signs (as in the control of the electric blanket), and lights (as in the personal fan). However, as intellectual disability relates to thought processes and communication skills, it affects memory, abstract thinking and interpretation, making it difficult for people with ID to understand these visual abstractions [58]. This is supported by some of the usability problems identified in this study (problem a.4, b.4 y c.7 in Table 5). In this line, it has been suggested that it is relevant for this population to include wider types of feedback such as audio, video or text [29,49].

4.4. Affordance

Avoid the use of double gestures in one button. Opt for discrete controls with distinct start and stop points, rather than continuous controls that may be harder to navigate accurately.

Several usability barriers were related to the affordance of the interfaces and PECS. Affordance, as defined by usability expert Donald Norman, is the relationship between an object's properties and the user's capabilities to determine how the object should be used [57]. In this experience, the use of double gestures in the same button for the large pedestal fan (tap for on/off, and twist for air speed) created severe confusion as the affordance of the control had one dominant gesture for interaction (tap for on/off), making it counter-intuitive for the participants. Additionally, adjusting the air speed through a continuous control also significantly confused the users as it was harder to control with precision, and it frequently went from the highest level to the minimum in one subtle hand movement. People with ID, and in this case, also older people with ID, struggle with fine motor skills, so it is easier for them to interact through discrete controls with limited numbers of air velocity or heat levels than with soft continuous controls.

4.5. Touch sensitivity

Avoid smooth or glazed surfaces that may activate with minimal contact. Utilize physical buttons that are easy to press without requiring significant strength.

Touch screens or similar buttons also posed many challenges for this audience, as they could not recognize certain elements as interactive or actionable and they were not able to successfully control the clicks and taps due to the high sensitivity of the touch buttons. This supports previous researches that have shown that people with ID struggle with accessing, selecting, or using different touch interfaces [56,59].

The large standing fan, which presented the highest number of control options, was the one that reported the highest frequency of barriers and severity of interaction issues. The advanced features, such as oscillation movement, the so-called "ecology" and "night" mode were used through a touch interface placed on the bottom of the fan, where the main control for power and air velocity was also placed. The interface design was driven by the current tendency for minimal design and clean look & feel, which are characteristics usually associated with desirable and novel technologies. However, such interface designs can undermine their usage and adoption by people with ID and other physical disabilities [56].

5. Limitations and future work

The sample size of eight participants is acknowledged as a limitation of the study. In usability research, Nielsen's recommendation to conduct usability tests with just five participants is widely accepted, as this sample size can uncover around 85 % of usability issues [60]. He argues that the number of issues identified increases rapidly, with key findings repeating when more participants are tested. However, there's debate about the validity of this assumption. Bevan et al. suggest that only the simplest issues are detected with such a small sample [61], while Faulkner argues that testing with 10 participants can already reveal in average the 95 % of issues, with a minimum of 82 % [62]. For this study, eight participants were deemed sufficient to identify initial usability issues, and more importantly, show the relevance of such studies with users with disabilities before planning more extensive and time-consuming research campaigns. Since several barriers were identified in this research, it is recommended in future studies to expand the number of participants and thermal PECS assessed.

As it has been shown in previous research, PECS for thermal comfort range from portable to background systems, and from low-tech to high-tech devices [10]. This research selected three conventional and affordable technologies for thermal comfort. Future work in this area should explore the usability of a larger number of typologies of PECS for thermal comfort, such as innovative wearable devices or smart textiles and technologies. This will help to gain a broader picture of potential barriers for usability.

Carrying out this usability study with PECS required multiple adaptations to the instruments to facilitate and promote the participation of people with intellectual disabilities (ID). Some of these adaptations included creating accessible informed consents, questionnaires with visual support that were validated and piloted before the test, and preparation of the participant group to familiarize them with key concepts of the research and training to adequately answer the daily questionnaire. Recent research has suggested that studies on thermal comfort tend to consider including a caregiver's perspective when conducted inclusively with people with ID [32]. However, this study supports the paradigm of inclusive research, which is based on the idea of empowering individuals with ID to exercise their right to have their own voice and vote [29,63–65]. The authors acknowledge that this approach may be a topic of discussion that deserves to be addressed in greater depth in future publications.

Future work should investigate the learnability curve of these technologies by repeating the same tests over a longer period and compare the level of task effectiveness, efficiency and satisfaction over time. In addition, safety concerns were addressed in just one interview during the pre-test questions of the usability test, specifically expressing concerns about the potential risk of burns from the electric blanket. However, this same participant later reported frequent use of the blanket at night during the winter, as noted in the post-season individual interviews. Nonetheless, safety should be a critical consideration in PECS, especially when they are used by people with intellectual disabilities (ID). Currently, numerous technological devices include warnings against use by individuals with physical or mental disabilities, often excluding this population from their intended user base. This exclusion could be viewed as discriminatory within technology design, according to the universal design and universal accessibility principles.

6. Conclusions

This research evaluated the usability of three off-the-shelf personalized thermal control systems in Chile (an electric blanket, a small personal fan and a large pedestal fan), with people with intellectual disabilities who live together independently in the context of energy poverty. The goal was to provide initial evidence on the importance of evaluating usability of thermal PECS with a users with ID, since usability can be a severe obstacle to the use and adoption of thermal PECS and,

ultimately, limit their effectiveness in improving thermal comfort.

The main conclusions from this study are.

- Two of the three PECS exhibited a poor performance in terms of usability for users with ID and several barriers to their use and adoption were identified;
- the large pedestal fan was the technology that presented the greatest and most severe usability problems among the participants due to the larger number of control option and features. After the large pedestal fan, the electric blanket and the small fan also presented usability problems in this study.
- In terms of anticipation, although the association between the small fan and feeling warm was less evident during the interviews and before use, the interaction turned out to be straightforward, effective and satisfactory during the season use.
- Usability problems were related to poor visibility, material, communication, bad affordance and touch sensitivity in the PECS interaction design due to the use of touch interfaces. Small details in technology became a barrier for people with ID, such as the case of the plug for the electric blanket.
- The level of adoption of PECS varied among participants, with the blanket showing in general little adoption from all the participants, the small personal fan showing widespread adoption and the large pedestal fan showing larger group adoption but little personal adoption, mainly because of usability barriers. These variations also suggest a spectrum of user engagement, from passive recipients to more empowered and curious adopters, from which for all usability is placed as a key factor for longer-term relationships with the devices.

Overall, this study showed that usability is a key requirement for thermal PECS, in particular because problems related to usability can hinder PECS adoption. In this sense, it is crucial to consider the requirements of a large and diverse group of users when designing the interfaces for personal control to enhance their adoption and usage. Users with ID represent a relevant population for studies on thermal PECS since they are highly vulnerable to excessively low or high temperatures. Therefore, a personal, tailored and local control of their thermal environment can be extremely beneficial to safeguard their health and comfort. Overall, several usability barriers encountered in this study could also be a barrier for users without ID. Nonetheless, following the recommendations of universal designs, if PECS are well-designed for meeting the requirements of users with ID, they will also have an easier adoption and usage by the users without ID.

CRedit authorship contribution statement

Katherine Exss: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Alessandra Luna-Navarro:** Writing – review & editing, Visualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Katherine Exss reports financial support was provided by National Agency for Research and Development ANID. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

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