Exploring Novice Approaches to Smartphone-based Thermographic Energy Auditing: A Field Study

Matthew Louis Mauriello[1], **Manaswi Saha**[1], **Erica Brown**[2], **Jon E. Froehlich**[1]
Makeability Lab | Human-Computer Interaction Lab
Department of Computer Science[1], Department of Bioengineering[2]
University of Maryland, College Park
{mattm401, manaswi, ebrown17, jonf}@umd.edu

ABSTRACT

The recent integration of thermal cameras with commodity smartphones presents an opportunity to engage the public in evaluating energy-efficiency issues in the built environment. However, it is unclear how novice users without professional experience or training approach thermographic energy auditing activities. In this paper, we recruited 10 participants for a four-week field study of end-user behavior exploring novice approaches to semi-structured thermographic energy auditing tasks. We analyze thermographic imagery captured by participants as well as weekly surveys and post-study debrief interviews. Our findings suggest that while novice users perceived thermal cameras as useful in identifying energy-efficiency issues in buildings, they struggled with interpretation and confidence. We characterize how novices perform thermographic-based energy auditing, synthesize key challenges, and discuss implications for design.

Author Keywords

Thermography; Mobile Devices; Formative Inquiry; Field Study; Sustainable HCI; Energy Efficiency

ACM Classification Keywords

H.5.m. Information interfaces and presentation (e.g., HCI)

INTRODUCTION

Improving energy efficiency in the built environment is an important global concern [54]. In the United States, for example, buildings account for 41% of primary energy consumption—more than any other sector—and contribute an increasing portion of carbon dioxide emissions (33% in 1980 *vs.* 40% in 2009) [38]. To reduce consumption and emission levels, the U.S. Department of Energy (DOE) recommends conducting energy audits to help identify sources of inefficiencies and make recommendations for renovations and retrofits. Home energy audits typically identify improvements that lead to 5-30% reductions in utility use [64]. Energy audit requirements are increasingly becoming part of city legislation [4] and building certification programs [37,62]. In response, interest in professional energy auditing has increased [35,52].

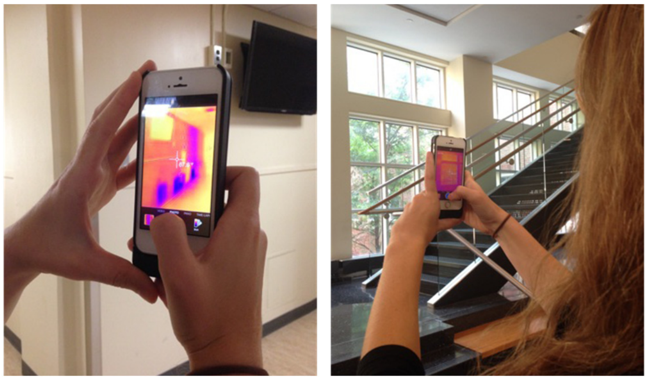

Figure 1: Smartphone-based thermal cameras present an opportunity to engage novice users in thermographic energy auditing activities, which could increase engagement in efficiency initiatives.

Professional energy auditors assess buildings using an array of diagnostic tests. With improvements in handheld infrared sensors and falling costs, auditors have been increasingly using *thermography* during energy audits [5,9,21,42]. Thermographic-based energy auditing is a data collection and a visual analytics technique that uses thermal cameras to help detect, diagnose, and document energy issues such as building defects and air leakage that produce thermal signatures (*e.g.,* areas of missing insulation) [47,51]. Prior work has shown that including thermal imagery, or *thermograms*, in end-user reports positively influences (homeowner) retrofit decisions and conservation behaviors [29,51]. However, despite technological advances, thermographic-based energy audits remain a laborious activity requiring training and expertise [47].

Recently, thermal camera attachments have emerged for smartphones, which have begun to broaden the adoption of this technology (Figure 1) [70,71]. Marketing materials suggest diverse use, including for DIY energy audits, art and electronics projects, and outdoor recreation (*e.g.,* see [72]). The release of smartphone-based thermal camera attachments—and even fully integrated smartphone thermal cameras [74]—has prompted the development of an increasing number of mobile apps that use and support thermography [22]. While still early, these trends foreshadow a future in which thermal cameras are ubiquitous—integrated into commodity electronics and part of a range of services and applications.

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In this paper, we conduct the first qualitative field study of thermal camera use by novices. As formative work, our research questions include: *How do novice users of thermal cameras assess the built environment? What attributes of the built environment do they focus on, learn about, and discover? What challenges do they encounter? What benefits do they perceive?* To explore these questions, we recruited 10 novice participants to take part in a four-week field study of smartphone-based thermal camera usage. Participants were asked to use their thermal cameras whenever and however they wanted. To help guide their auditing activities, participants were also asked to complete weekly thermographic "missions" with specific themes: the home, the workplace, commercial buildings, and the community. At the end of each week's mission, participants submitted their thermal imagery and completed a survey about their activities. The study concluded with semi-structured debrief interviews with participants.

Our findings suggest that novice users can use thermal cameras to document energy-efficiency issues in buildings and to find previously unknown problems. Our participants also reported a general heightened awareness of electrical energy use and a greater likelihood of engaging in energy conservation practices (complementing findings of [29,51]). However, participants had difficulty gauging the severity of the issues they uncovered making it difficult to determine the impact of energy-efficiency improvements. Reflecting on our findings, we discuss barriers to novice thermographic energy auditing as well as design implications for both Sustainable HCI and public auditing of the built environment.

In summary, the contributions of this work include: (i) the first study of how novices approach using thermal cameras within the context of energy auditing; (ii) a synthesis of key challenges novices experience when collecting and interpreting thermal imagery; and (iii) a discussion of implications for future thermographic systems. Our work should be of interest to Sustainable HCI researchers, designers, and those working energy auditing.

BACKGROUND AND RELATED WORK

We provide background on energy auditing, trends in thermographic research, and links between thermography and Sustainable HCI. We also describe work relevant to thermal cameras as tools for public energy initiatives.

Energy Auditing and Thermographic Assessment

Energy audits are performed for many reasons including to verify that buildings are operating efficiently and/or to identify sources of inefficiencies [64]. Audits frequently begin with a walkthrough inspection to collect information about a building's construction, on-site appliances, safety, and environmental comfort. This information is combined with historical utility data and may be used to predict the expected financial return on investment on efficiency recommendations.

As noted in the introduction, thermographic-based energy audits are becoming more common due to the increased availability of thermal cameras and their decreased cost. Thermal cameras work by detecting the electromagnetic radiation emitted by all objects above absolute zero [27]. The thermal data is automatically combined with images from a conventional camera to produce a contextualized thermal image or *thermogram*. Energy auditors use thermal cameras to measure surface temperatures in walls, roofs, ceilings, and other parts of a building's envelope while looking for inconsistent patterns, discontinuities, and other anomalous heat signatures that may indicate the presence of an efficiency issue [9,42].

While thermographic scanning can be beneficial during energy audits (*e.g.,* to detect the location of air leakages), there are limitations to the technique that impact data accuracy such as wind and intensity of sun. According to ISO standards, thermal scans should be conducted only when a minimum temperature differential of 14°C between a building's interior and exterior can be established [36,65]. Additionally, blower doors, a type of door-mounted fan, are often helpful to intensify airflow and increase the visibility of thermal signatures during data collection [21,63]. Beyond the need to assess or configure the environment, data collection and analysis is often a subjective process relying on the training and experience of the auditor [46]. This subjectivity has led to calls for developing more quantitative methods and tools for collecting and analyzing thermal imagery [65].

While novice users now have increased access to thermal cameras, there has been no examination of how they approach using this technology or what challenges they face when interpreting thermal imagery. Due to the subjective nature of thermographic energy auditing, it is unclear whether novices can perform thermographic energy audits, especially in absence of tools designed specifically with them in mind. In our work, we explore how novices use thermal cameras within the context of thermographic energy auditing and how their participation impacts their understanding of energy use and the potential for building energy efficiency improvements.

Thermograms as Eco-Visualizations

In addition to being a diagnostic tool, another primary reason for capturing thermal imagery during energy audits is that it serves as an effective *eco-visualization,* helping to reveal otherwise invisible information about energy flow [55]. Prior work has found that persons who reviewed thermal imagery from their household audits were nearly five times more likely to make retrofit decisions [29] and that viewing thermal imagery encourages energy conservation behaviors [51]. One explanation for these findings is that thermal imagery provides a "particularly compelling" reason to consider retrofit recommendations and behavior changes by surfacing invisible issues and making them seem more tangible [35]. However, these studies have been performed in the context of larger interactions between professional auditors and clients [35,47]. Thus, it is currently unclear how beneficial novice end-users will find their personally collected and interpreted imagery without professional guidance, which this study begins to address.

Trends in Thermographic Research

While using thermography during energy auditing activities is viewed as beneficial by professional auditors, collecting and analyzing thermal imagery is typically seen as laborious and costly [47]. Thus, researchers have explored ways to both scale-up collection and improve human interpretation of the data. For example, using automatic [7,16,43] and semi-automatic [44] robotic systems as data collection platforms to scalably audit urban areas. Touted advantages include manual labor reductions, increases in the volume of data, which can enable new types of analyses, and the ability to safely survey inaccessible or potentially hazardous areas (*e.g.,* building rooftops) [43,44]. However, professional auditors argue that these approaches, while scalable, are not able to configure an environment for capture, tend to capture only partial views of exterior building facades, and analysis of the collected imagery remains time consuming [47]. Closer to our work is the development of human-oriented solutions such as hand-held and wearable data collection tools [49,50,66], augmented reality devices [15], and thermographic analysis software [31]. Our work explores the potential for novices to perform DIY thermographic energy audits via emerging smartphone-based thermal cameras, which would scale thermography along a new dimension: end-users.

Sustainable HCI

Since its emergence at CHI in 2007 [6], a large portion of Sustainable HCI literature has centered on curbing CO2 emissions through the design of *eco-feedback* [25] and *persuasive* [23] technologies (see surveys [10,19,41]). These technologies frequently focus on monitoring resource consumption (*e.g.,* electricity [2], water [26]) or promoting sustainable practices (*e.g.,* use of public transportation [24], recycling [14]) that can influence emission rates. Looking specifically at home energy consumption, research has shown that technology-based interventions can reduce energy consumption by 4-12% [20]. Commodity thermal cameras and their interactive capture and analysis software offer building occupants a potential new resource to learn about energy use and inefficiencies, particularly for otherwise overlooked areas like detecting poor insulation and window/door sealing. As Gardner and Stern note [28], humans place a disproportionate focus on *curtailment behaviors*, which involve forming new routines to reduce environmental impact (*e.g.,* turning off lights when leaving a room), rather than one-time behaviors such as upgrading insulation, which provide a lasting impact and are far more significant to improving efficiency. Thermal cameras can uniquely aid in the latter, especially in cases where occupants have the ability to make changes to their environment [10,40].

Our specific interest is to explore the use of thermal cameras as an empowerment technology that allows users of varying skill to investigate, analyze, and report building energy efficiency issues [40]. As formative work, our research shares similar aims to other qualitative Sustainable HCI studies (*e.g.,* [18,30,68]): to understand how this technology is used and identify what role HCI may play.

Smartphone-based Public Auditing

One long-term research focus is investigating how commodity thermal cameras may be used to engage end-users in citizen science initiatives—for example, in using thermography to help audit largescale infrastructures in cities. However, to date there have been only limited attempts to engage the public in energy auditing tasks [1,33]. Smartphones, our focus, are often used by the public to perform volunteer audits on a range of topics, including noise pollution [59], air conditioning use [57], potholes [48]. Smartphones are particularly attractive tools for public auditing projects because they are relatively accessible, provide lightweight computing capabilities to support task completion, and generate easily shareable data. Similar to *SeeClickFix*, a smartphone app for capturing and reporting infrastructural issues to city governments [69], our work begins to explore the idea that thermographic energy audits can be performed by the public across use-contexts (*e.g.*, home, workplace) [55].

FIELD STUDY: NON-PROFESSIONAL THERMOGRAPHY

To investigate how novices use thermal cameras for energy auditing and how they interpret thermal imagery, we conducted a four-week field study with 10 participants during the winter months of 2015. Each participant was provided a *FLIR ONE* thermal camera attachment (Figure 2) for their personal smartphone and told to explore freely throughout the study. To help guide their auditing activities, participants were also asked to complete weekly

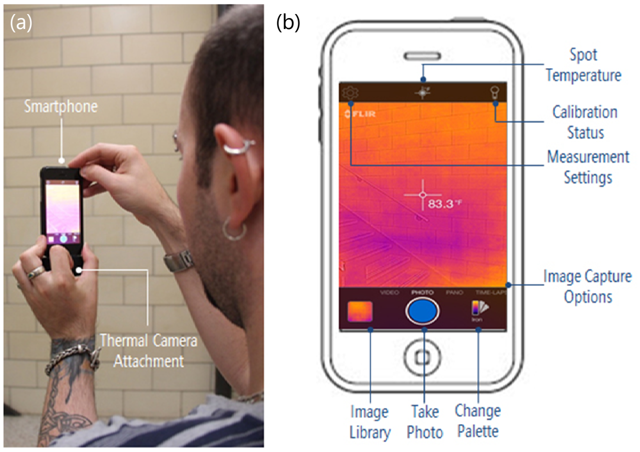


Figure 2: (a) A thermal camera attached to an iPhone 5. **(b)** A close-up of the standard FLIR ONE camera application that ships with the attachment.

thermographic "missions" (adapted from the prompting method in [58]). Missions were included to scaffold and motivate data collection across a range of use-contexts: home, work, and two public spaces. Prior work informed our study design [47] as did our pilot studies [45] where we found that missions helped structure auditing activities and think more broadly about places to capture thermal imagery. To help us understand participant activities, participants answered an online questionnaire and uploaded their thermograms weekly. At the end of the study, participants were debriefed via a semi-structured interview and compensated with $100.

Field Study Equipment

The FLIR ONE thermal camera attachment is widely available—sold at Apple Stores and online—and fits a wide range of iPhone models. As shown in Figure 2a, the thermal camera attaches to the iPhone's Lightning port. For our study, participants used the FLIR ONE thermal camera application, which looks and largely functions like a conventional camera application with a "Take Photo" button in the center and a list of image capture options (Figure 2b). The display updates in real-time; photos can be taken at any time but the camera works best in a stable position. The user can change how the camera colorizes the thermal data (*i.e.,* the "Change Palette" button). In the example shown, the "Iron" palette is used which displays colder regions in the image in shades of purple and warmer regions in shades of orange. The icons on the top menubar allow users to change measurement settings, display a temperature measurement tool (*i.e.,* average temperature in in the crosshairs), and see when the camera is calibrating.

Field Study Method

Participants

We recruited 10 participants (5 female) from the general population using local mailing lists and community message boards (Table 1). Our recruitment ad specified that we were interested in studying smartphone-based thermal cameras for energy auditing. Potential participants completed a short eligibility questionnaire. We screened for adults (ages 18+) and compatible smartphones. Participants were enrolled on a first-come, first-served basis.

To collect demographic information and understand attitudes toward environmental sustainability, participants completed a short, pre-study questionnaire. In general, our participants were eco-conscious and concerned about the environment. Using 7-point Likert scales ordered from *very unconcerned* (1) to *very concerned* (7), participants reported being very concerned about climate change, concerned about the energy efficiency of their homes and their local community, but less concerned about their workplace—see Table 2. Additionally, half (*N*=5*)* reported regularly engaging in conservation behaviors (*e.g.,* turning off lights) and making minor efficiency modifications in their homes (*e.g.,* upgrading light fixtures). Some (3) reported making large efficiency improvements (*e.g.,* installing solar panels). A few (2) reported making minor changes to solve winter comfort issues (*e.g.,* sealing drafty windows with plastic). Participants reported no previous experience with thermal cameras; however, a few (3) previously had professional energy audits of their homes; two included thermography.

ID	AGE	GENDER	EDUCATION	PROFESSION	IPHONE
P1	22	Female	Bachelor's	Public Affairs Specialist	6
P2	25	Female	Bachelor's	Graduate Student	6
P3	30	Male	Master's	Graduate Student	5s
P4	58	Female	Doctorate	Research Scientist	5s
P5	31	Female	Master's	Higher Education Professional	6s
P6	56	Male	Master's	Government Scientist	5
P7	28	Male	Master's	User Experience Designer	6s
P8	53	Male	Master's	Marketing Coordinator	5
P9	34	Female	High School	Education Coordinator	6
P10	40	Male	Master's	Educator	6

Table 1: A summary of the participant's demographic information.

CONCERN	AVERAGE
Climate Change	6.5 (SD=0.8, Mdn=7.0)
Home	5.3 (SD=1.2, Mdn=5.5)
Community	5.2 (SD=1.5, Mdn=5.5)
Workplace	4.8 (SD=1.5, Mdn=4.5)

Table 2: The pre-study survey asked participants how concerned they were about climate change and the energy efficiency of specific contexts in their daily lives.

WEEK	MISSION
Home	Investigate your home with your thermal camera for signs of energy inefficiencies and comfort issues; collect at least 25 photos that highlight aspects of your investigation.
Workplace	Investigate your workplace to help inform new policies on energy conservation and comfort; collect at least 25 photos that highlight aspects of your investigation.
Commercial	As if you were a building inspector, investigate a commercial location (e.g., a café) for potential issues based on your previous experience; collect at least 25 photos that highlight aspects of your investigation.
Community	As if you were a municipal inspector, investigate your local downtown or community area; collect at least 25 photos that highlight aspects of your investigation.

Table 3: Weekly mission descriptions were sent to participants via email along. Lightweight feedback about the previous week was also provided.

Procedure

Introductory briefings were held in our lab or in a local café, depending on participant preference. Upon arrival, a research assistant discussed the study plan, obtained consent, provided the thermal camera and accessories (*e.g.,* manufacturer's documentation), and reviewed a 4-page custom training document (see Supplementary Materials). The document was synthesized from thermal smartphone applications [22], how-to guides from manufacturers [73], and DOE materials [63,64] by a research team member with a professional thermography certification; it covered key elements of a successful thermographic investigations.

Participants were encouraged to freely explore objects, their environment, or anything that struck their interest with their thermal cameras. To help structure and motivate their explorations, we also provided them with weekly energy-themed missions. The missions ranged from home inspections to community explorations; see Table 3. All participants received missions in the same order. At the end of each week, participants uploaded their photos and completed an online questionnaire about their experience.

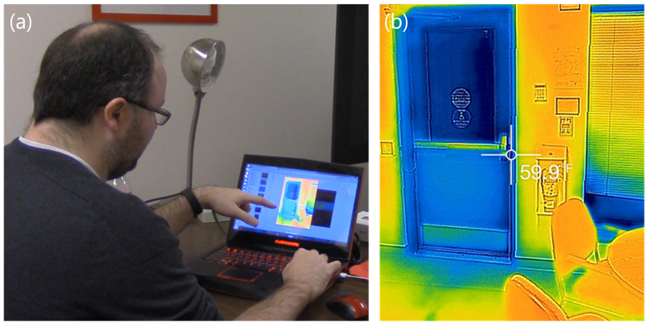


Figure 3: (a) A participant describes an air leakage issue found while auditing his workplace during the post-study debrief interview. **(b)** A close-up of the actual thermal image being discussed.

At the end of week four, participants participated in an in-person, semi-structured interview with a photo-elicitation component [13]. During the photo-elicitation, participants used their thermogram collection as a visual aid to help recall and describe experiences (Figure 3). Except where the interviewer had marked a photo for discussion, participants chose which photos to discuss. After the photo-elicitation, participants described their experiences over the four-week study, including discussions about how current thermal cameras could be used by non-professionals and improved to better support them in the future.

Data and Analysis

Images and interviews were qualitatively coded. Counts and descriptive statistics were calculated for survey data.

Images. In total, participants took 1,991 thermographic images; however, 83 of these images (4.2%) were invalid because either the thermal camera was calibrating when the image was taken or the image was indecipherable (*e.g.,* a thumb blocking the camera lens). To determine what participants were taking pictures of, the remaining 1,908 images were analyzed through an iterative coding method using both inductive and deductive coding [8,34]. Multiple codes could be applied to the same image. We first selected and coded a random participant's image dataset (*total images*=139). The initial codebook was composed of a list of expected objects and contexts (*e.g.,* window, outdoor) and a miscellaneous code that allowed researchers to tag unforeseen yet significant elements within the images (*e.g.,* pet). Two researchers independently coded each image. Cohen's Kappa (κ) was used to measure inter-rater reliability (IRR). IRR on the first iteration of the codebook was κ=0.57 (*SD*=0.23) suggesting it required iteration [67]. The two researchers met, resolved disagreements, and updated the codebook accordingly. Both researchers then coded a second, randomly selected participant's image collection and achieved an IRR of κ=0.80 (*SD*=0.20) with codes ranging from *strong* to *near perfect* agreement. Our final codebook included 19 codes grouped into four categories: *subjects* (*e.g.,* electrical device), *context* (*e.g.,* indoor), *biologic* (*e.g.,* animal), and *misc.* (*e.g.,* clutter). The remaining images were then split between the two researchers and coded independently. The final codebook is included in our Supplementary Materials.

Weekly Surveys. The weekly surveys captured feedback on each mission such as: a description of what participants found during their assessment activities and recommendations, if any, that they might have to improve building performance. The surveys also asked for procedural details such as the date and duration of their audit activities. Finally, participants filled Likert-scale questions about their experience using the thermal camera. The survey took approximately 30 minutes to complete.

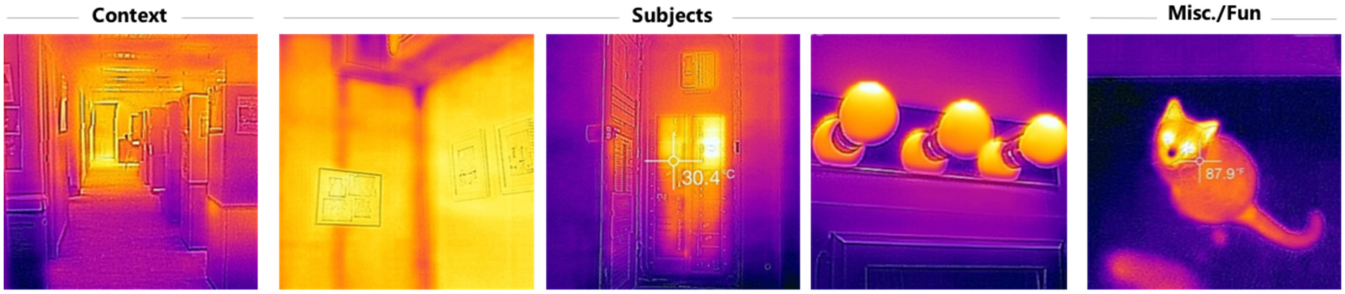
Debrief Interviews. The semi-structured interview sessions lasted an average of 75 minutes (*SD*=18.2). Interviews were audio recorded and professionally transcribed. Similar to the image analysis, we pursued an iterative coding approach using a mixture of inductive and deductive codes. Two researchers explored the interview transcript of a randomly selected participant using an early codebook developed based on research literature, our study protocol, and discussions amongst the research team. The final codebook included 12 codes grouped into three categories: *experiential* (*e.g.,* exploratory behavior)*, design ideas & challenges* (*e.g.,* design idea), and *broader impact* (*e.g.,* potential benefit). The unit of analysis was the response to a single question or image. IRR on the first iteration of the codebook was κ=0.51 (*SD*=0.21). Again, the two researchers met and resolved disagreements. This was repeated with randomly selected transcripts three times achieving an overall IRR of 0.87 (*SD*=0.08); remaining transcripts were split and coded. Again, the final codebook is included in Supplementary Materials.

Field Study Results

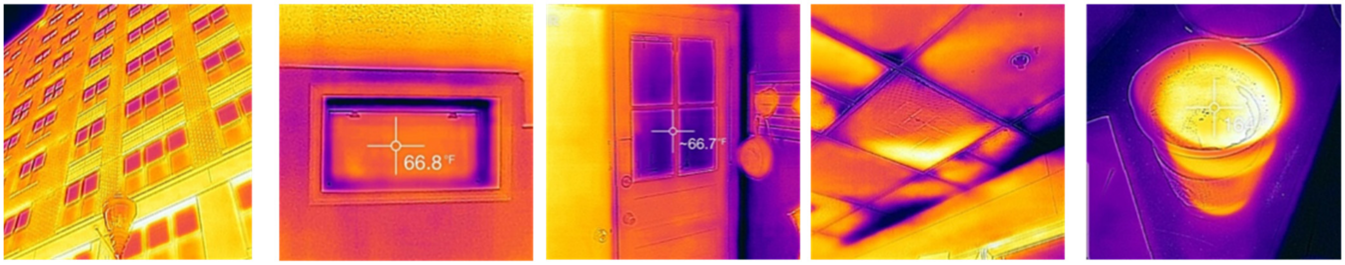
We first provide an overview of the field study activities. Next, we review each mission based on the weekly survey responses and captured images. After presenting the field study results, we address our research questions through thematic analysis of the entire corpus of study data. Finally,

Weekly Mission	Image Totals	Avg. Images Per Participant	Avg. Time Spent (mins)	Avg. # Audit Sessions	Avg. Mission Difficulty	Thermal Camera Helped w/ Learning	Thermal Camera Helped w/ Identification
Home	572	57.2 (*SD*=52.27)	34.9 (*SD*=15.02)	1.9	5.3 (*SD*=1.25, *Mdn*=6.0)	5.9 (*SD*=1.19, *Mdn*=6.0)	5.4 (*SD*=0.66, *Mdn*=5.5)
Workplace	405	40.5 (*SD*=18.02)	32.0 (*SD*=14.59)	2.0	4.4 (*SD*=1.26, *Mdn*=4.5)	5.4 (*SD*=0.32, *Mdn*=6.0)	5.2 (*SD*=0.32, *Mdn*=5.5)
Commercial	415	41.5 (*SD*=9.72)	28.7 (*SD*=16.77)	1.7	4.2 (*SD*=1.39, *Mdn*=3.5)	6.3 (*SD*=0.67, *Mdn*=6.0)	5.9 (*SD*=1.19, *Mdn*=6.0)
Community	516	51.6 (*SD*=26.73)	29.7 (*SD*=13.69)	2.1	4.5 (*SD*=1.26, *Mdn*=4.5)	5.5 (*SD*=0.84, *Mdn*=5.5)	5.0 (*SD*=1.05, *Mdn*=5.0)

Table 4: An overview of participant behavior and survey responses. Average time spent was calculated by adding the total minutes spent across all data collection sessions in a given week based on participant's self-report data. For Likert questions, we used a 7-point scale ordered from *strongly disagree* (1) to *strongly agree* (7); 4 was neutral. We report median (*Mdn*=X) and standard deviation (*SD*=X). For mission difficulty, higher is easier.



(a) Indoor (64.2%) (c) Walls (71.6%) (e) Electronics (24.7%) (g) Light Fixtures (23.8%) (i) People/Pets (4.7%)



(b) Outdoor (35.6%) (d) Windows (30.3%) (f) Doors (24.4%) (h) Ceilings (22.7%) (j) Play/Experiments (1.0%)

Figure 4: Examples of the image contexts, subjects, and non-mission photos as well as the percentage of the dataset that includes these features.

we present participant design considerations for future thermographic tools. Participant quotes are attributed using a 'P' followed by their identification number (*e.g.,* P1).

Overview of the Four Auditing Missions

To characterize participant activities during the missions, we examined: what participants took pictures of, how much time participants spent performing their auditing activities, and the perceived utility of the thermal camera. For the latter, participants reported how helpful they felt the thermal camera was for learning about and identifying energy-related issues during audits. Table 4 presents specific details for each mission, which we summarize next.

Data Collected. Participants took 47.7 photos per mission, most commonly containing walls (71.6% of images), windows (30.3%), doors (24.4%), and electrical devices (23.7%). Participants concentrated on interior inspections (64.2 %) rather than outdoors. See Figure 4 for examples.

Time Spent. Participants typically spent 1.2 hours completing each mission, which was often divided across multiple days (usually 2). Participants reported spending 30 minutes capturing thermal imagery and another 30 minutes on reporting (*i.e.,* completing the weekly survey). The remaining time was spent planning (*i.e.,* what building to audit) and uploading imagery to the research team.

Thermal Camera Utility. Overall, the thermal camera was deemed helpful in identifying and learning about potential problems in buildings, particularly for the first three missions (Home, Workplace, and Commercial).

Individual Auditing Missions

In each of the four missions, participants were asked to explore a different location. Here we briefly describe results from each mission before discussing pervasive themes.

Home Mission. In this mission, participants investigated their homes looking for potential energy inefficiency issues. Half of the participants (5) investigated single-family homes, three investigated town homes, and the remaining two investigated apartment units. In the post-mission survey, all participants (10) reported checking for window, door, and insulation issues. Most participants (8) started with pre-existing comfort issues (*e.g.,* rooms that were not adequately heated or cooled). A few (3) explored electrical appliances (*e.g.,* dryer) due to a safety concern. Additionally, a few (2) investigated a friend's home.

Based on their auditing activities, several participants (4) concluded that the windows in their homes needed minor repairs (*e.g.,* improved air sealing), a few (3) reported insulation issues, one was motivated to contact an electrician, and the rest (2) did not report finding any issues. As a positive example, in the post-mission survey, P7 reported exploring a pre-existing thermal comfort problem and that the thermograms made him "*very confident about missing insulation issues, especially in the ceilings of that room*" (Figure 4a). Thus, the participant decided, "*I would like to share this image with my landlord,*" to see if this issue could be addressed.

Workplace Mission. In the second mission, participants explored energy use in their workplaces. Most participants (7) investigated office buildings, two investigated university buildings, and another investigated a local grocery market. Like the Home Mission, all participants (10) reported looking for leaky windows, doors, and noted interest in the heat signatures produced by electronics. Two participants did not report finding any energy efficiency issues. Three reported finding leaky windows and doors, and five reported finding electronic devices using phantom energy (Figure 4b). As P4 explained:

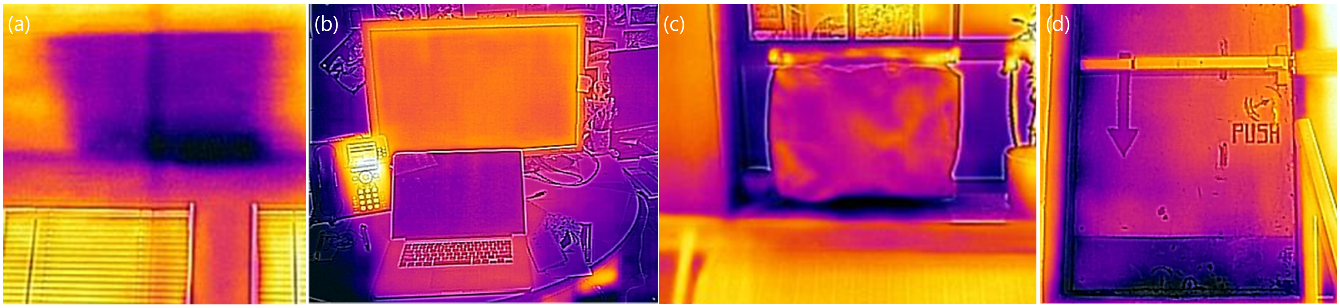


Figure 5: Example imagery from participant investigations: **(a)** insulation issue in roof of a residential home, **(b)** observing power consumption of computer equipment in an office, **(c)** gathering evidence of insufficient winterization procedure of window air conditioning units in a university building, and **(d)** documenting the need to repair weather stripping around an emergency exit door at a community theater.

> *"I was stunned to realize that my monitor doesn't completely turn off when it goes to sleep. It was unused for the weekend but still appeared hot. So I turned it off when I went to lunch and when I came back and it was indeed cooler." –P4*

As in the Home Mission, two participants used thermal comfort as motivation to explore their workspace. For example, due to this mission being conducted in the winter season, P5 noted that many offices in her building were cold and that she used the thermal camera to confirm her suspicion: *"I found that most of the ceiling vents were colder which leads me to believe they might still be pumping out cool air."* Thus, P5 concluded that her workplace's air conditioning settings might need to be adjusted. P10 described a similar shared concern about how drafty his workplace became because of insufficient air conditioning unit winterization procedures and used his thermal camera to investigate (Figure 5c). Based on his imagery, he concluded:

> *"The situation with the window A/C units is absurd. Honestly, they should be removed in the fall and reinstalled in the spring since it is so hard to insulate them and they are only needed during the summer. Having that much air getting through in the summer is also a problem, we just don't realize it and continue running the units." –P10*

At the time of the debrief interview, P10 reported that he was considering sending the imagery to his facilities management to help evaluate the problem.

Commercial Mission. The third mission asked participants to explore a commercial building. Participants investigated a wide range of establishments from restaurants to hardware stores. Seven participants did not report finding any evidence of potential efficiency issues. Unlike the previous missions, participants were not able to use their knowledge and experience of a place to guide their explorations (*e.g.,* where cold drafts were located). Most participants (9) investigated equipment such as storage, food preparation, and serving areas found in commercial cafés or markets. One participant found potential evidence of moisture damage in a restaurant. Two reported finding evidence of leaky windows and doors. For example, P8 investigated a community theater and reported finding air leakage issues prompting a discussion with the operators (Figure 4d):

> *"The theatre underwent went a major renovation in 2014-15 where it was closed for several months. ...In speaking with the operator, she indicated that although there were all new exteriors doors and windows on the main level, the upstairs office windows and fire doors were original." –P8*

P8 reported sharing his thermal photographs with the operators, who planned to send the images to city officials to show the need for further repairs.

Community Mission. The final mission was open ended; participants were asked to investigate their local community, which they mostly did outdoors. Nine participants did not report finding any issues but did describe finding and learning about utility infrastructure in their community such as water lines and electrical equipment (Figure 6a). P4 additionally explored a local makerspace and reported (Figure 6b):

> *"The makerspace was a treasure trove: clear differences between new and old windows, where patches of the walls were made (cold sources), evidence of water damage (confirmed by renter of the space), and old pipes creating cold spots on the walls and ceiling." –P4*

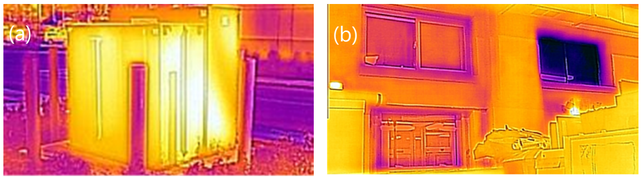


Figure 6: During the community mission, participants learned about utility infrastructure **(a);** one explored a makerspace **(b).**

Summary. During the first three missions, participants primarily investigated buildings for missing insulation, air leakage issues, and understanding phantom energy use. In the home, participants seemed comfortable drawing conclusions about the need for repairs. In each mission, a small number of participants indicated that they wanted to address discovered problems by contacting a landlord, an electrician, or building owners/operators. In the final mission, participants used their cameras to explore their community and, most did not find concerning issues; however, they mostly took exterior pictures of buildings.

Major Themes Across Missions

While the previous section characterized participant behavior on a per-mission basis, we now turn toward describing themes that emerged across our four-week study, including: how participants collected and interpreted thermal imagery, what they learned, and what influenced their ability to act on their findings.

Data Collection. Rather than following any specific plan or procedure as an expert auditor might do [61], all participants (10) described their investigations as random walks through the interior of buildings. Participants occasionally followed their interior walk with another around the building's exterior, and participants who were aware of pre-existing issues tended to start in those areas. This was especially true during the home and workplace missions. With no pre-existing issues in mind, participants described their activities as exploratory, often using the camera as an augmented reality lens into otherwise invisible energy flows. As P1 said:

> *"I was mostly just looking through the lens of the camera. I wasn't looking at my surroundings and then putting a camera up. I was holding the camera up and taking photos." – P1*

When looking through the live view of the thermal camera, if participants discovered what they perceived as an anomalous heat signature, they would then take two-to-three images from slightly different positions or angles to ensure adequate capture. Even if they did not find anything of interest, participants would still take one or two wide-angle photographs to help them record areas that they investigated. Due to the time it took to attach the camera and load the thermal app, most participants did not report taking many photos outside of the mission scenarios.

Interpretation. When asked about interpreting thermal imagery, participants described how they appraised an image and things that made this task challenging. To determine if an anomalous heat signature was an issue, all (10) participants described looking for areas of high contrast in the images. Participants believed they could readily identify air leakages around windows and doors as well as the heat signatures from electronics; however, participants also described capturing imagery that they did not understand such as the cause of a warm spot on a wall that did not have any obvious source. While participants were not always able to describe what made interpreting a thermal signature difficult, most participants (8) attributed difficulties to the presence of confounding objects (*e.g.,* heating elements), materials (*e.g.,* metals), and other environmental factors (*e.g.,* sunlight). For example, referring to an image P3 said:

> *"This is all glass, so it's reflective. It's not clear to me if it's really that much warmer on the inside of this building than the outside." –P3*

All (10) participants said that at times they lacked confidence in their ability to draw appropriate conclusions from the thermal images. Most participants (6) found it difficult to determine the severity of issues they found and the potential impact repairs would have on the efficiency of the building. As P2 described, *"I don't know how much [the issue] really affects the energy use of my apartment."* Additionally, half (5) of the participants suggested that a lack of information about a building (*e.g.,* age) and/or its construction (*e.g.,* type or rating of insulation used) limited their ability to draw confident conclusions.

Knowledge Gains. Through their use of the thermal camera, all participants (10) reported learning to identify hidden structures or common issues in the built environment such as hot water pipes or leaky windows. Many participants (6) also stated that they learned about how materials had different conductive or reflective properties. P3 said: *"I certainly learned about the thermal reflectance of common surfaces, that's something that I had not known before."*

Awareness of Energy Efficiency. In the debrief interviews, seven participants described how their perspective on the way buildings are used and maintained had changed. We classified these perspectives into two categories, related to *energy consumption* (5) and *building maintenance* (2). participants frequently mentioned that seeing the easily recognizable thermal signatures from electronic devices forced them to consider electrical use and conservation. For example, P10 found that thermal images were a helpful reminder to turn off devices that are left on standby (and consuming phantom energy [56]):

> *"It's one of those things that I'm aware of in theory: when you leave things plugged in there is still some energy use, but seeing it like this reminds me about it." –P10*

However, a few participants also pointed out that there are many "*always on*" devices that do not have a convenient way to manage their energy consumption (reaffirming [12]), including their internet routers at home or the phone systems common in office environments. Two participants noted that their perspective on building maintenance had changed. P6, for example, had come to believe that inspections and building efficiency maintenance should be an ongoing practice, like with a car:

> *"It's one of these things you've got to keep working at to incrementally find, you know, I can do something more efficiently here, turn this off more, or fix that problem." –*P6

Perceived Value of Thermography. All (10) participants perceived value in having a tool that helped them investigate potential energy-related problems in buildings. Most (8) suggested that thermal imagery could provide supporting evidence to building owners and or others in charge of building maintenance. For example, P3 stated *"I've been meaning to contact my landlord with these images and say, look, there seems to be a clear issue here that I think you should address."* Two participants suggested thermography might be useful for community related improvements. As P2 described:

> *"It would be interesting to go and do this in the local high school and see if it's built well, that we're not wasting energy*

> *and resources that we could be using for something else... I feel like if there are ways that we could save on energy by repairing things, then that would be beneficial." –P2*

Locus of Control. Two main issues were raised about making energy improvement decisions: lack of control and apathy. Some participants (4) who rented or lived in housing cooperatives were concerned that if they found evidence of a problem that they would not be in a position to make retrofit decisions. As P5 stated, "*If I took a picture that showed an insulation issue, I don't necessarily think the owner would get on top of fixing it."* In missions outside the home, one participant expressed that it was not clear who they should talk to if they discovered an issue. In response to performing a mission in a local café, P2 asked:

> *"If I find an issue, who am I going to tell and are they really going to care? My biggest concern is what if something is wrong and they don't want to do anything about it." –P2*

While locus of control issues are non-trivial, especially in residential buildings where asymmetric power relationships may exist with landlords (*e.g.,* [10,60]), thermal cameras may play a unique advocacy role for tenants to highlight otherwise difficult-to-observe problems or provide continued evidence of an unresolved issue.

Participant Design Considerations

At the end of the debrief interview, participants were asked for suggestions to improve smartphone-based thermography tools. Participants discussed support for automation, privacy, and general usability improvements.

Automated Assistance. Similar to our findings with professional auditors [47], most participants (8) suggested adding "intelligent" mechanisms that would help them collect and analyze thermographic data. For example, participants wanted the live camera view to automatically identify anomalous thermal signatures as well as provide an estimate of problem severity and the amount of money saved if addressed. P9 summarized:

> *"You want to make sure that you are in a very energy efficient area, so that you're not wasting and not spending too much money. Does making a change really help save energy costs? These are things I am interested in learning." –P9*

Privacy. While three participants had no concerns, half of participants (5) indicated they would adopt their normal digital photograph sharing practices for the thermograms. Two participants who had investigated the homes of others during the study considered those thermograms to be potentially sensitive, and felt that they would need to ask for permission to share. P3 summarized:

> *"All the photos from Missions 2, 3, and 4, I have no problem sharing. The ones from my friend's house I wouldn't want to share period; it's not my house to share. The ones from my house I'd be fine sharing online." –P3*

Usability. Most participants (9) wanted the thermal camera to be fully integrated with their smartphones due to the perceived tediousness of retrieving and connecting the attachment. Participants speculated that this change would make them more likely to perform explorative activities.

DISCUSSION

As the first qualitative, human-centered inquiry into novice approaches to smartphone-based thermographic energy auditing, our findings demonstrate that novice users with minimal training can use thermal cameras to detect potential energy efficiency issues in the built environment; however, that they often lacked confidence in correctly interpreting thermographic imagery and understanding the severity of problems they identified. Furthermore, our findings described: (i) how novice users collect and interpret thermal imagery, (ii) challenges that impede their auditing activities, and (iii) design considerations that could guide the development of future thermographic systems. Below we reflect on our findings, suggest future work, and discuss limitations.

Reflection on Method: Mission Structure

In this study, we asked novices to freely explore their environment using a thermal camera as well as complete structured weekly missions (adapted from [58]). While the mission structure may have prompted certain behaviors that would otherwise not have been observed, they also allowed participants to explore different scenarios, motivated data collection, and helped keep participants engaged over the four-weeks. We believe that these methods enabled us to extract meaningful data, and would be appropriate for studying similar technologies in the future within specific use scenarios like ours. Follow-up work may want to explore completely unstructured thermal camera use in the wild.

Barriers to Novice Thermographic Energy Auditing

While novice users perceived value in their use of thermal cameras, they also highlighted several potential barriers to utilization of this data, which we discuss here.

Knowledge and Experience. Future systems designed for novice use will need to consider how to assist them with performing thermographic inspections and interpreting thermal imagery. As noted by [47], professional thermographers suggested that knowledge of building materials, construction practices, and thermographic measurement procedures (*e.g.,* ISO standards) are critical to performing a good thermographic scan. Future applications could provide the needed scaffolding during data collection activities (*e.g.,* via on-screen prompts). Tools that support novice analysis of thermographic data could help generate recommendations with assistance from automation, social networks, or professionals; this might help reduce the experiential gaps between thermographers.

Decision Making. With the emergence of low-cost thermography tools, end-users will likely play an increasingly active role in energy auditing activities. Participants observed that thermal cameras were useful for detecting problems (*e.g.,* air leakage around windows or doors) and, as others have noted [47,52], to perceive energy use in buildings. However, participants also expressed concern about not always knowing what to do with the information they obtained from their audits. Particularly in cases where users have the locus of control necessary to implement changes, it will be important to understand how to bridge the gap between information and action (*e.g.,* through actionable recommendations) [32]. Future, more longitudinal work should investigate how likely novice auditors are to implement their self-generated recommendations, particularly in the home, and if energy efficiency improvements are achieved.

Locus of Control. It is important to consider the limits of a user's ability to effect change outside of their immediate locus of control (or use-contexts [43]). The barriers to effecting change expressed by our participants are consistent with the findings of other researchers who examined the role of social factors in energy consumption and building maintenance [12,13]. In contrast to a professional energy auditor whose services are requested unless the user is the owner or operator of the building, it may be difficult for them to make changes—particularly structural upgrades, improved insulation, and the purchase of energy-efficient appliances. As building energy efficiency is increasing as a priority [4,37,62], authorities may give more credence to issues with sensor-based evidence such as that from a thermal camera. Future work should investigate how to assist end-users with verifying their sensor-based recommendations and advocating for having issues addressed.

Privacy and Sharing. Thermal images can contain identifiable and sensitive information. Participants expressed concern about sharing thermal images (similar to those raised about conventional photographs [2]) and considered the social implications—questioning their right to share imagery that contained data they considered owned by others—and about who else the data would be shared with. These concerns also mirror those raised by professional energy auditors [35]. Our work suggests that future thermographic systems should investigate anonymization and privacy protection.

Implications for Public Auditing

With the increasing availability of thermal cameras, our work begins to explore scenarios in which motivated citizenry can use thermography to audit public infrastructure—perhaps, to increase transparency and accountability. Our findings suggest that novice auditors will likely perform best in scenarios that have clearly defined goals (*i.e.,* Missions 1–3) and that their approach will likely focus on recording potential issues rather than the lack thereof—though both are important. This finding is consistent with other novice data collection communities (*e.g.,* citizen science [39,53]). Given emerging examples of citizens using thermal cameras in energy and pollution monitoring contexts as a form of whistleblowing [11,17], novice thermography use for social causes is a potentially rich area for future Sustainable HCI research.

Limitations

Our study had four primary limitations, which should be addressed in future work. First, our participants were eco-conscious and highly educated, which may have influenced their perceptions and interpretations of thermography as well as their willingness to suggest taking actions. However, our participants likely represent early adopters making their feedback and experiences valuable. Second, as our participants were involved in a semi-structured study, our findings may not translate to general, unguided use of these tools. Third, while a trained thermographer reviewed participant data, we did not attempt to systematically verify or study the accuracy of participant diagnoses based on their thermal images. Finally, some participants discussed making retrofit decisions or conversing with building operators (*e.g.,* landlords) based on their thermographic findings; however, we did not conduct follow-ups, so we do not know what (if any) actions took place.

CONCLUSION

This paper contributes the first qualitative investigation of novice approaches to smartphone-based thermographic energy auditing. Through a four-week field study of end-user behavior, we assessed the efficacy of novice thermographic energy auditing activities across different use-contexts. Our findings indicate that participants perceived thermal cameras as effective diagnostic tools and suggests that novice imagery could be an impactful form of Eco-Visualization. Through our semi-structured interviews, we identified important challenges and potential benefits of engaging novices in thermographic energy auditing. Our findings have implications for both the design of future thermographic tools and for Sustainable HCI researchers working in energy efficiency. Cheap, emerging thermal cameras have the potential to broadly impact the way we interact with and understand our built environment—from residential homes to commercial buildings [3].

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