Designing and Evaluating Next-Generation Thermographic Systems to Support Residential Energy Audits

By Matthew Louis Mauriello

August 1st, 2018

Professor Jon E. Froehlich, Chair/Advisor
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MAKEABILITY LAB
Human Computer Interaction Laboratory
COMPUTER SCIENCE UNIVERSITY OF MARYLAND
UNIVERSITY OF MARYLAND

What does energy use look like in the United States?

Transportation (28%)

Industry (32%)

Buildings (40%)

Most (95%) of building in the United States are residential and approximately a quarter (25%) of their energy consumption goes toward heating or cooling.


1413

Common reasons for **building inefficiencies** include their design, materials, and age.

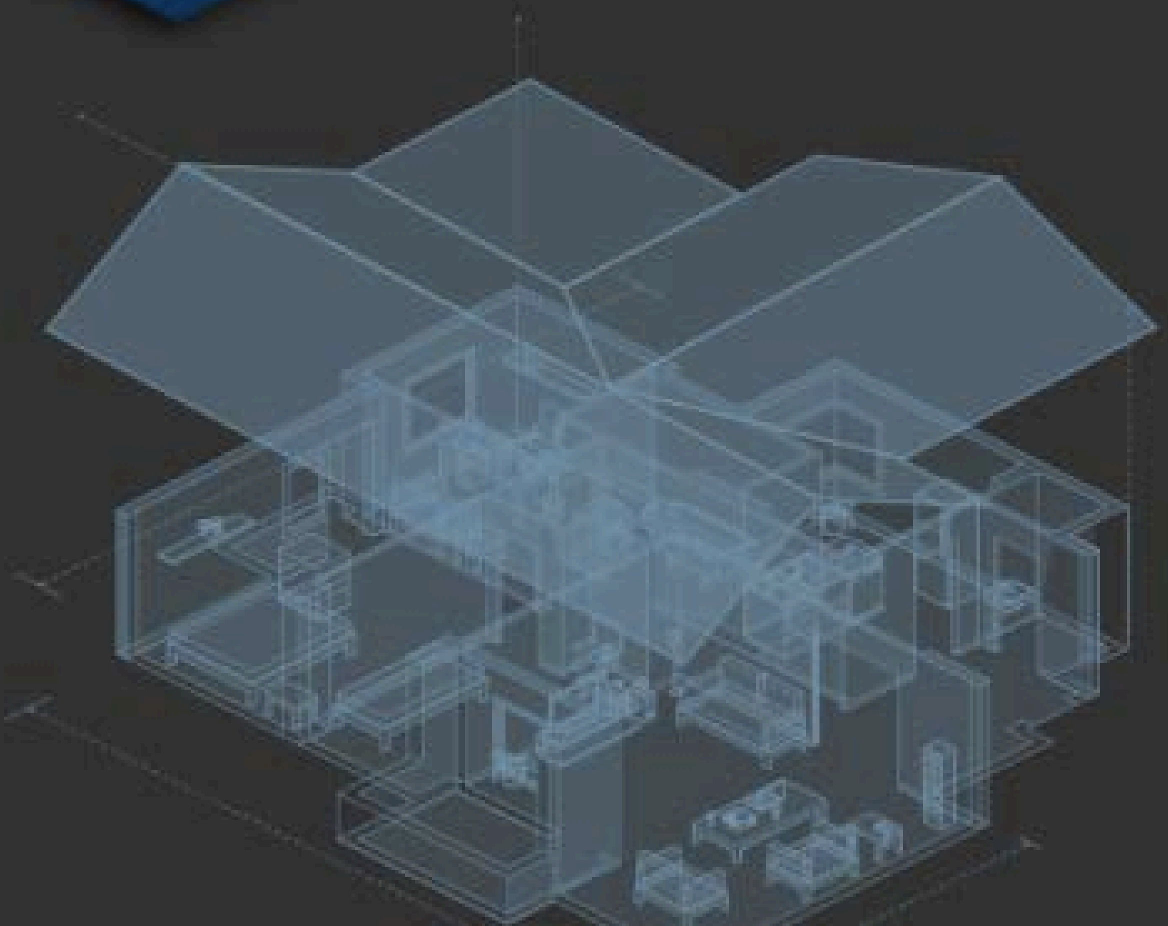
To address these issues, **renovations and retrofits of existing building stock** has become a pressing need.

The **US Department of Energy (DOE),** for example, has set a goal of **reducing housing energy use by up to 70%.**

Norberg-Bohm, V. and White, C. Building America Program Evaluation. 2004

Energy Saver 101:
Home Energy Audits

Take the first step to improving your home's energy efficiency: get a home energy audit.



What is a home energy audit?

A home energy audit helps you pinpoint where your house is losing energy and **what you can do to save money**. A home energy auditor will also assess health and safety issues that might exist in your home.

The audit involves two parts: the **home assessment** and **analysis** using computer software.

Thermographic Inspections

June 25, 2012 - 3:27pm

WHAT DOES THIS MEAN FOR ME?

Energy auditors may use thermography -- or infrared scanning -- to detect thermal defects and air leakage in building envelopes.

RELATED ARTICLES

Professional Home Energy Audits

Energy Audits

Home Energy Audits Can Help You Keep That New Year's Resolution

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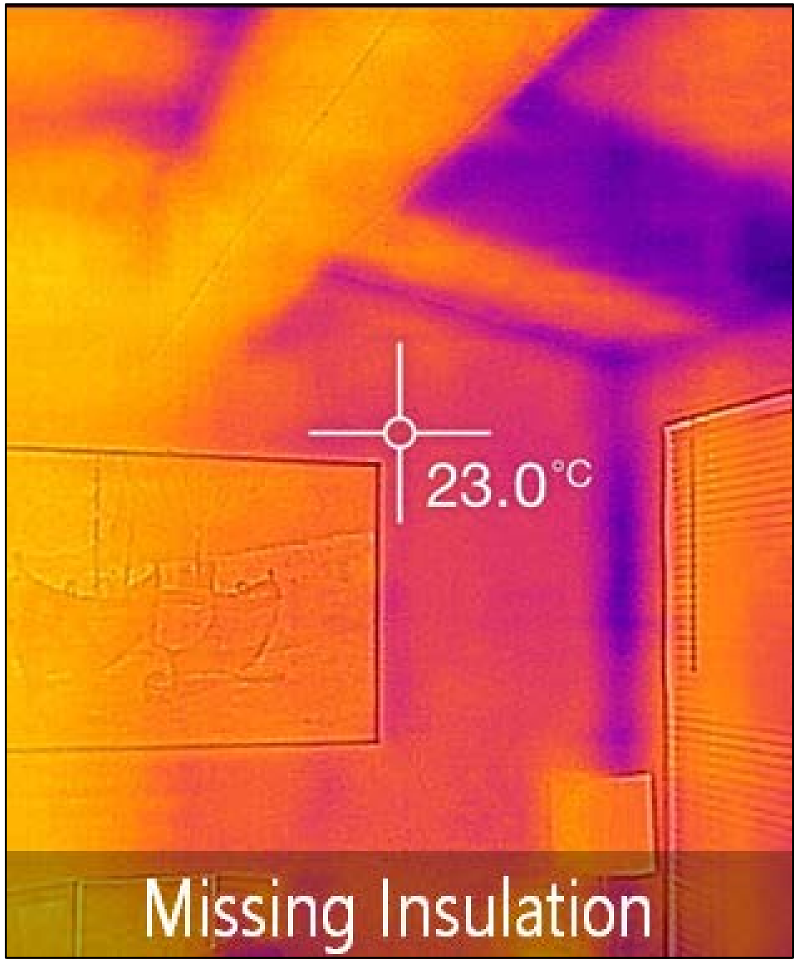
Thermal Cameras

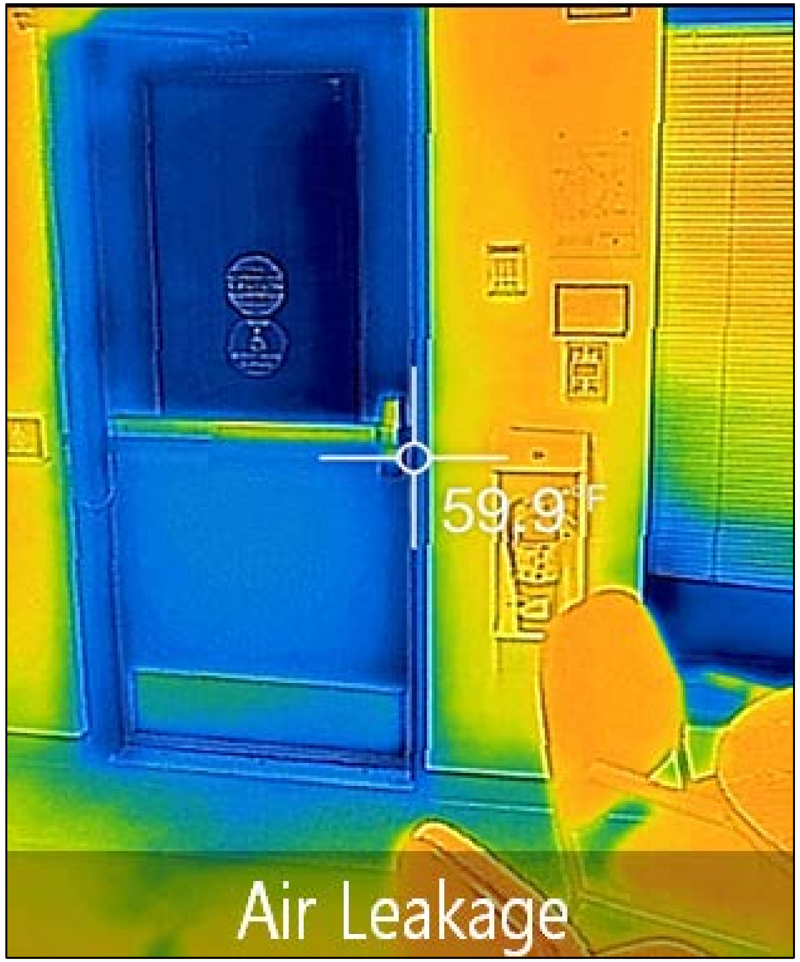
- Thermal cameras (or infrared cameras) detect electromagnetic radiation with lower frequencies than visible light (*i.e.*, infrared frequencies)

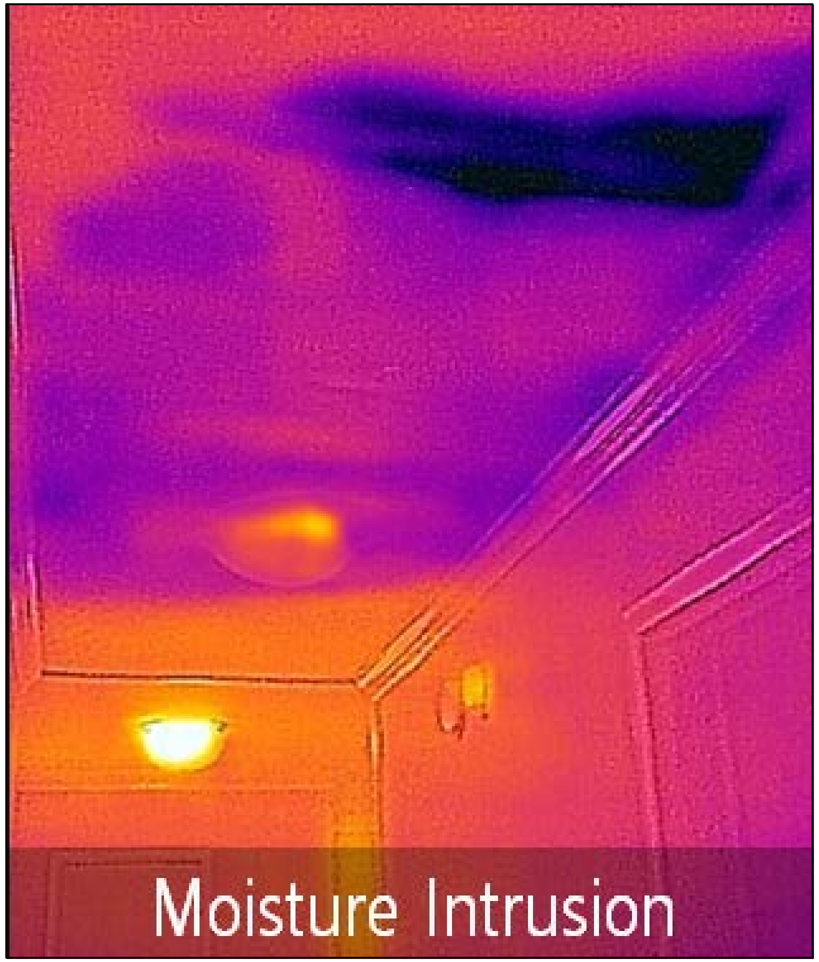
- All objects above absolute zero emit infrared radiation, so thermal cameras can ‘see’ in the dark without external illumination.

- The amount of radiation emitted by an object increases with temperature, so thermal cameras can also measure heat.

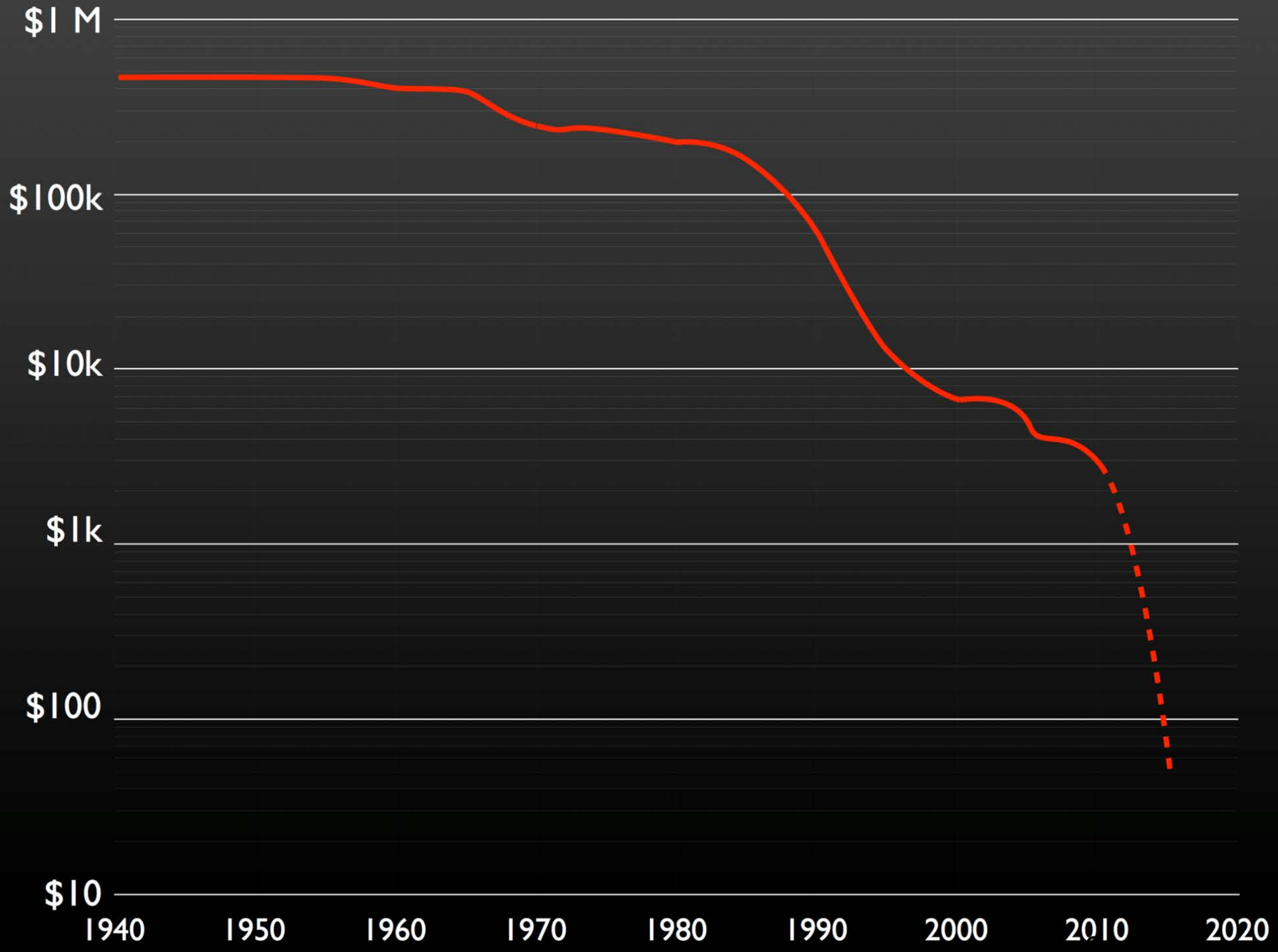
Common Thermographic Issues



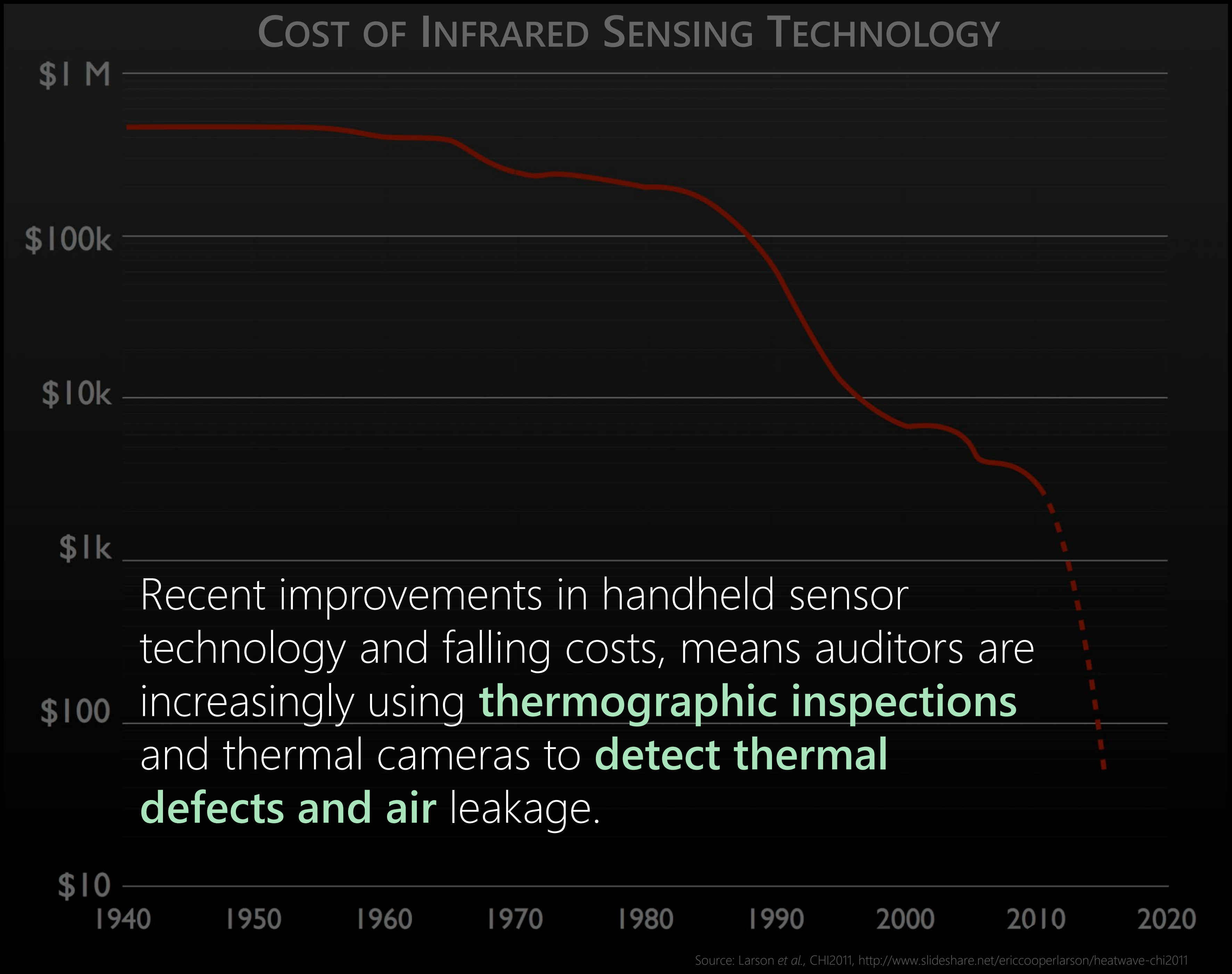




Cost of Infrared Sensing Technology



Source: Larson *et al.*, CHI2011, http://www.slideshare.net/ericcooperlarson/heatwave-chi2011


COST OF INFRARED SENSING TECHNOLOGY
$1 M
$100k
$10k
$1k
$100
$10
1940
1950
1960
1970
1980
1990
2000
2010
2020
Recent improvements in handheld sensor technology and falling costs, means auditors are increasingly using thermographic inspections and thermal cameras to detect thermal defects and air leakage.
Source: Larson et al., CHI2011, http://www.slideshare.net/ericcooperlarson/heatwave-chi2011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FLIR Approved Applications

In addition to the official FLIR apps, we've built a showcase of the best of breed apps written for the FLIR ONE. When your app achieves FLIR Approved App status, it will automatically be added to the gallery.

Featured App

Boat Beacon for FLIR ONE

by PocketMariner

Boat Beacon uses AIS to show the positions of ships around you when at sea including bearing and distance and closest point of approach (CPA). It also has a Marker button (MOB) which you can use to mark a spot and track its location. Boat Beacon's Augmented Reality view shows the ship positions, a thermal view, and MOB overlaid on the live Camera view. *Available Now !*

The Apps listed on this page have been reviewed and approved by FLIR and have been given the "FLIR Approved" status, which is verification that the App conforms to FLIR's corporate guidelines and policies for appropriate content and user experience. FLIR does not review the App for compliance with intellectual Property rights, safety, or other potential factors that may result in liability to the Developer. Thus FLIR disclaims any and all liability that may arise through a third party's use of the App or whether the App will meet any quality standard or level of merchantability.

FLIR ONE App

Provides a simple user interface with a variety of functions for operating your new FLIR ONE device.

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What does FLIR Approved app mean and what's the process for getting an app approved? Find out here ▸

FLIR Certified Developer Program

FLIR Certified Developers are trained by FLIR on thermal imaging and FLIR ONE developer tools. Want to become one of the elite certified developers? Learn more on the process ▸

iPhone Apps | iPad Apps | Android Apps

Apps for Android

Baby Monitor for FLIR ONE
by Mobile Toys & Tools
This application monitors your baby during sleep and raises alarm if he/she is out of rectangular Region of Interest defined by you.

CompassEye with FLIR
by Electric Pocket
A Professional Bearing Compass designed to help navigate at sea and used much like a pair of Compass Binoculars. When held vertically it shows the real-time camera view with a compass, bearings and artificial horizon overlaid, when flat it shows a real time map centred on where you are with the bearings and compass overlaid.

NovaVision
by NovaCoast
NovaVision utilizes the thermal image processing from the FLIR One to create thermal goggles for the user. The screen is divided in half and each half contains an image view, where the content comes directly from the FLIR One.

Remote Thermal Cam f. FLIR ONE
by Sven Killig
Remote Thermal Cam is a useful Android app that lets you use Your FLIR ONE as a Webcam for Your PC by sending an MJPEG stream to a SmartCam server via WiFi.

Thermal Camera for FLIR ONE
by Georg Friedrich
Thermal Camera uses the Flir One v2 to display a live infrared image. To achieve this task it uses its own render mechanism, that uses the 14bit raw data from the Flir SDK. Due to the nature of this implementation it can add new features, which are Flir independent.

Thermori-on
by matfydub
Thermori-on is a thermal musical instrument, inspired by the "Tenori-on", and using your FLIR thermal imaging camera.

ThermoVisual Motion Detector
by Mobile Toys & Tools
ThermoVisual Motion Detector (TVMD) is an intelligent, easy to use application that detects thermal and/or visual motion or changes automatically by using FLIR ONE infrared camera.

Thermal Paint for FLIR ONE
by Whale Tale Games
With Thermal Paint you can draw areas of the thermal image on top of the aligned visible-light image from the FLIR One. Highlight important areas of an image, or get creative and create unique works of art.

The Energy Efficiency Information Gap

Palmer *et al.* 2013

1 - 3% of residential buildings are audited each year.

Common recommendations include:

- Sealing air leaks
- Adding insulation
- Improving lighting
- Increasing efficiency of appliances

Including thermal imagery in reports increases the likelihood of implementing recommendations.

Energy Efficiency (2013) 6:271–292
DOI 10.1007/s12053-012-9178-2

ORIGINAL ARTICLE

Assessing the energy-efficiency information gap: results from a survey of home energy auditors

Karen Palmer · Margaret Walls · Hal Gordon · Todd Gerarden

Received: 4 June 2012 / Accepted: 18 October 2012 / Published online: 4 December 2012
© Springer Science+Business Media Dordrecht 2012

Abstract Commercial and residential buildings are responsible for 42 % of all U.S. energy consumption and 41 % of U.S. CO_2 emissions. Engineering studies identify several investments in new energy-efficiency equipment or building retrofits that would more than pay for themselves in terms of lower future energy costs, but homeowners and businesses generally do not have good information about how to take advantage of these opportunities. Energy auditors make up a growing industry of professionals who evaluate building energy use and provide this information to building owners. This paper reports the results of a survey of nearly 500 home energy auditors and contractors that Resources for the Future conducted in summer 2011. The survey asked about the characteristics of these businesses and the services they provide, the degree to which homeowners follow up on their recommendations, and the respondents' opinions on barriers to home energy retrofits and the role for government. Findings from the survey suggest that the audit industry only partially is filling the information gap. Not enough homeowners know about or understand audits, and the follow-through on recommendations once they do have audits is incomplete. But the survey findings suggest that low energy prices and the high cost of retrofits may be more resp… for these outcomes than failures of informatio…

Keywords Energy efficiency · Climate change

JEL classification L94 · L95 · Q40

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Washington, DC 20007, USA
e-mail: walls@rff.org

Introduction

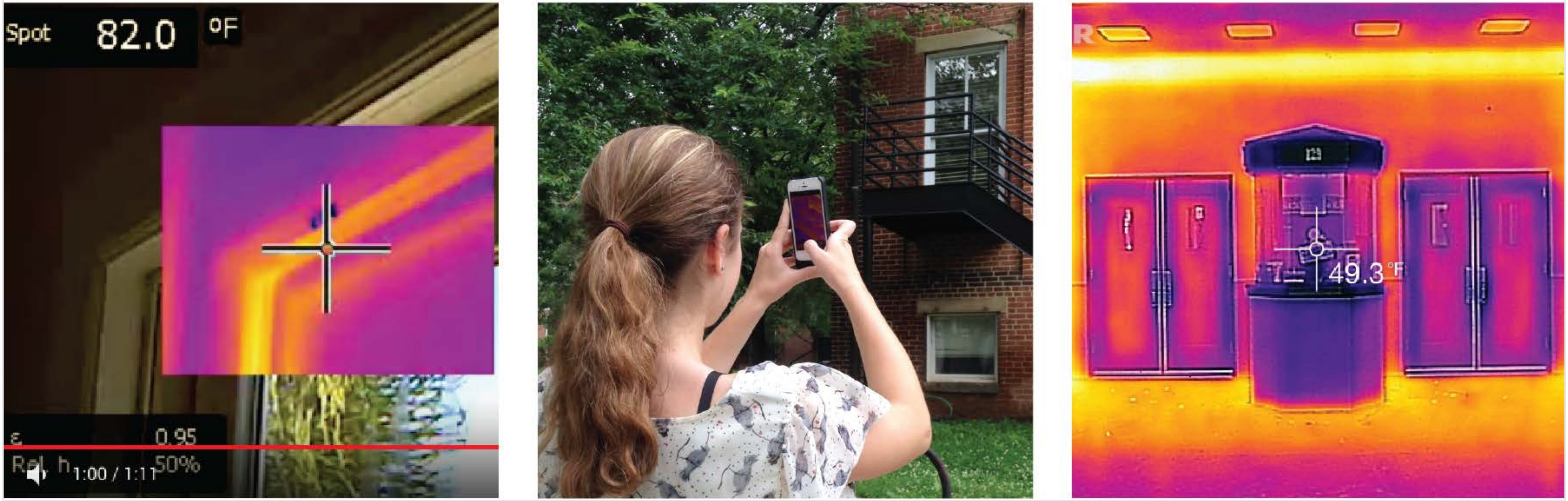
As the U.S.A. searches for ways to reduce emiss… of carbon dioxide (CO_2) to address concerns a… global warming, policymakers and others are focus… their attention on reducing energy consumption… buildings. Commercial and residential buildings… responsible for about 40 % of U.S. energy consum… tion and CO_2 emissions (EIA 2012). As a result… building codes, appliance standards, and general tec… nological improvements, new buildings tend to b… much more efficient than existing buildings. A hom… built in the 1940s consumes, on average, 50.8 thou… sand British thermal units (mBtu) per square foot, even with improvements that have been made over the decades since it was built. In comparison, an average home built in the 1990s consumes only 37.7 mBtu/ft² (U.S. Department of Energy 2008). The Joint Center for Housing Studies (2009) estimates that 40 % of residential energy consumption is attributable to homes built before 19…

Energy audits and thermographic surveying are time and labor intensive

Dissertation Overview

DISSERTATION OVERVIEW

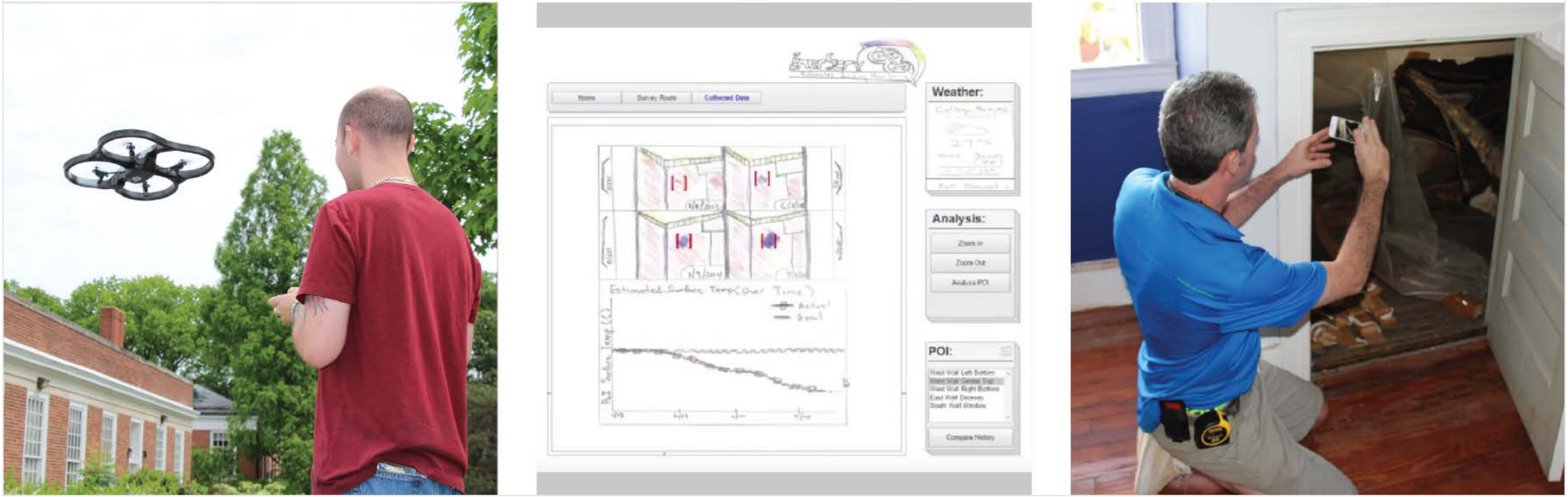
Research Thread 1: Studies of Novices Thermal Camera Use and Thermographic Energy Audits



Formative studies to understand and characterize current thermography **practices, benefits, and challenges** among **novice users**.

Dissertation Overview

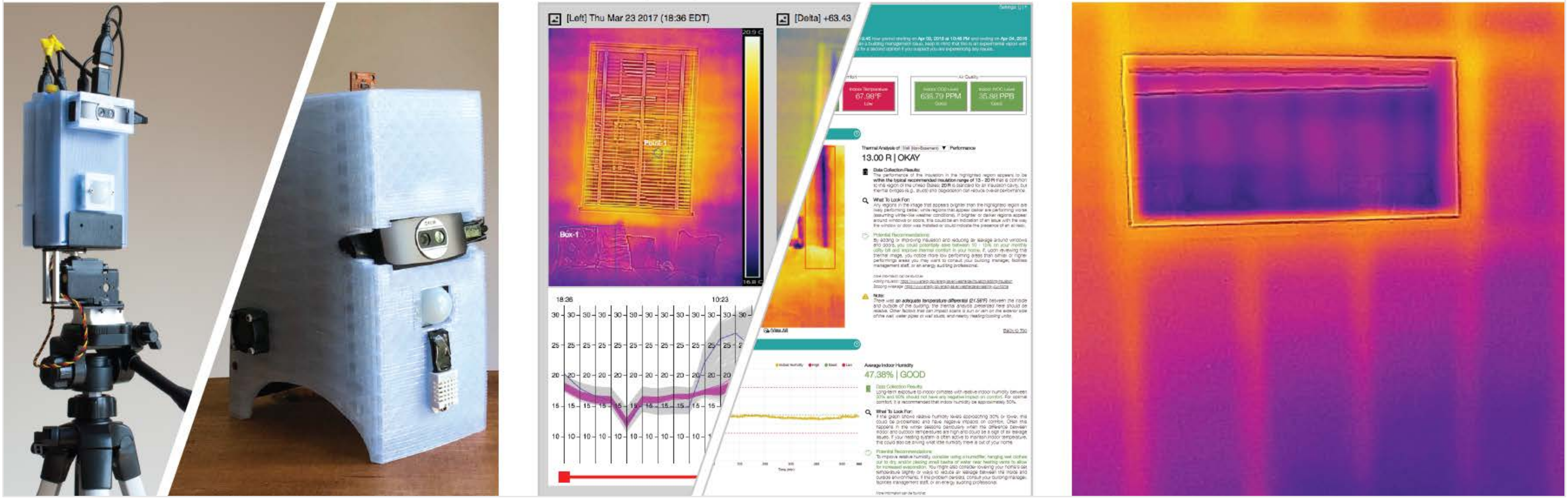
Research Thread 2: Studies of Professional Energy Auditing and Thermographic Automation



Explorations into the role of **thermography in professional energy auditing**, the **potential for automation**, and **pervasive thermographic scanning** in the built environment

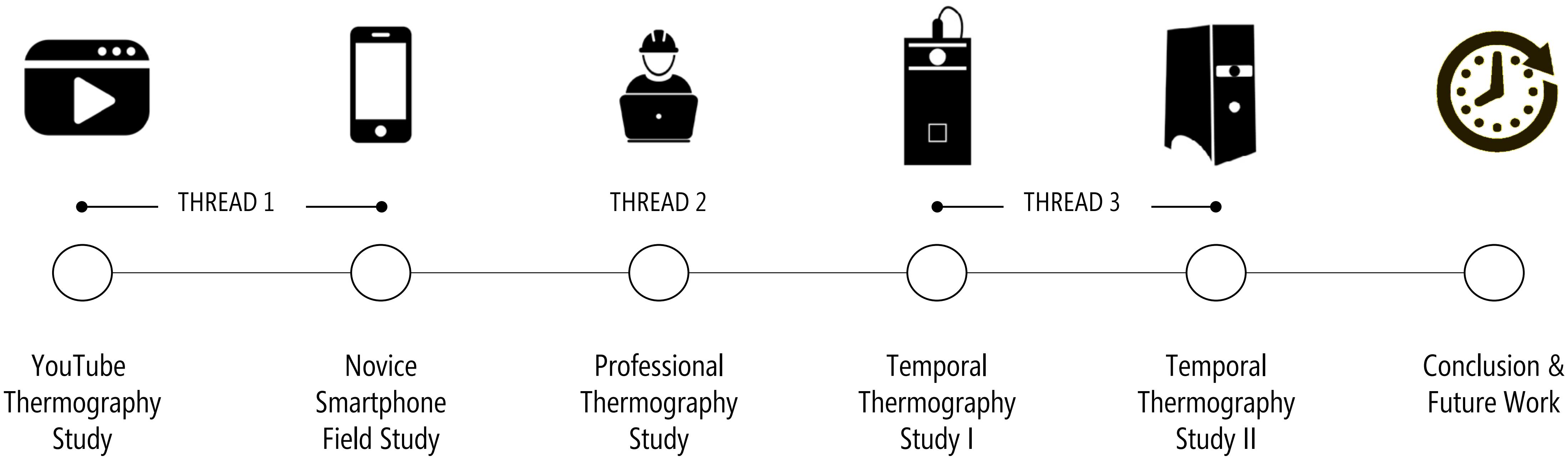
Dissertation Overview

Research Thread 3: Development and Deployment of a Longitudinal Thermographic Sensor System

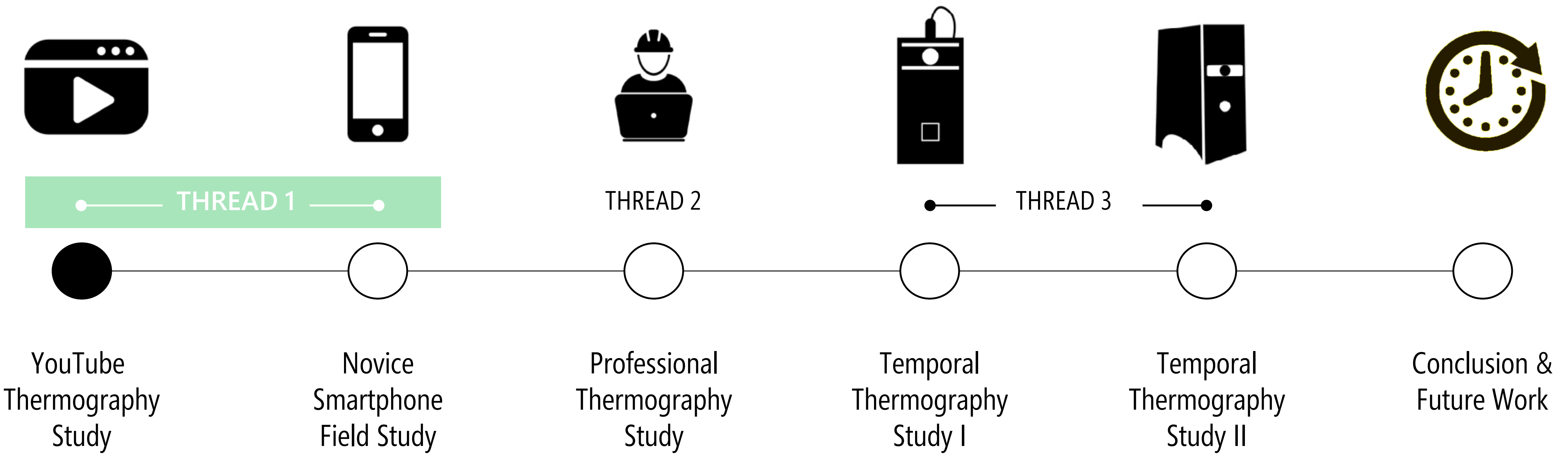


Advancing the state-of-the-art through the **development of novel, interactive building thermography systems** and deployment testing with both **novice and professional energy auditors**.

DISSERTATION OVERVIEW



Dissertation Overview




10:48
6:54
3:13
THERMAL FARTS
1:56
2:17
4:33
DAILY LIFE
2:10
6:51
PARANORMAL
Short
3:38
2:41
6:57
$40,000 THERMAL CAMERA
FLIR C2 / C3
3:00
FROZEN ENGINE THERMAL CAMERA
4:44
INFRARED BURNOUT
3:22
215-396-8452
water was hiding.
2:11

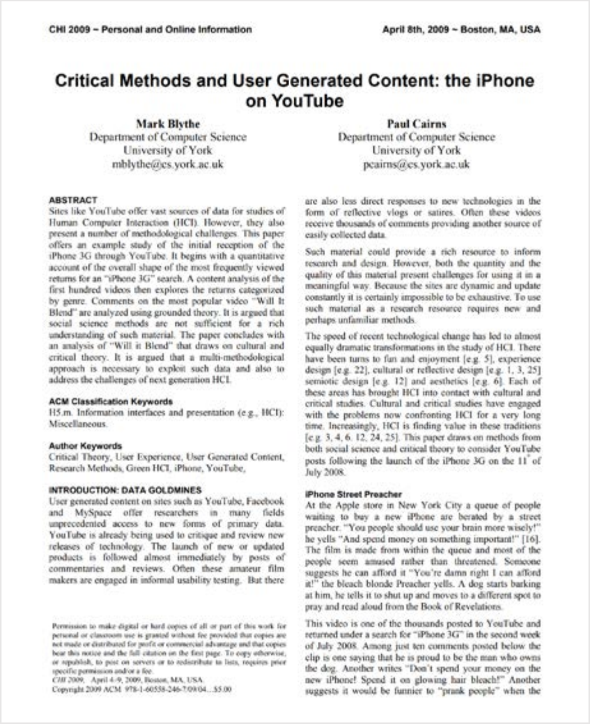
YouTube Study: Research Questions

1. What activities do non-professional users of mobile and handheld thermal cameras engage in and why?

2. What level of understanding about the technology is demonstrated?

3. How might these observations inform the design of future thermographic technologies?

RELATED WORK: DIGITAL ETHNOGRAPHY VIA YOUTUBE

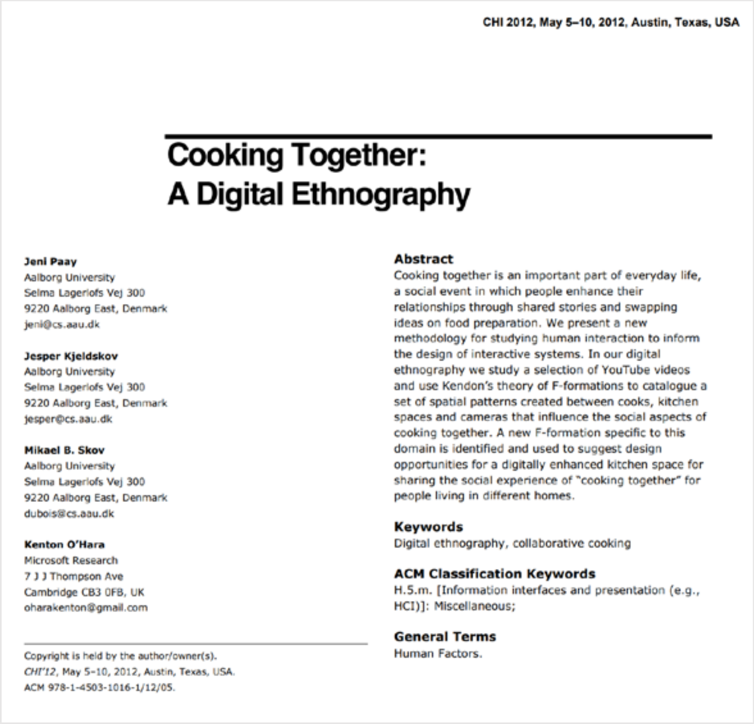

CHI 2009 ~ Personal and Online Information April 8th, 2009 ~ Boston, MA, USA

Critical Methods and User Generated Content: the iPhone on YouTube

Mark Blythe, Department of Computer Science, University of York, mblythe@cs.york.ac.uk

Paul Cairns, Department of Computer Science, University of York, pcairns@cs.york.ac.uk

Specific Technology
Blythe & Cairns 2009


CHI 2012, May 5–10, 2012, Austin, Texas, USA

Cooking Together: A Digital Ethnography

Jeni Paay, Aalborg University, Selma Lagerlofs Vej 300, 9220 Aalborg East, Denmark, jeni@cs.aau.dk

Jesper Kjeldskov, Aalborg University, Selma Lagerlofs Vej 300, 9220 Aalborg East, Denmark, jesper@cs.aau.dk

Mikael B. Skov, Aalborg University, Selma Lagerlofs Vej 300, 9220 Aalborg East, Denmark, dubois@cs.aau.dk

Kenton O'Hara, Microsoft Research, 7 J J Thompson Ave, Cambridge CB3 0FB, UK, oharakenton@gmail.com

Abstract

Cooking together is an important part of everyday life, a social event in which people enhance their relationships through shared stories and swapping ideas on food preparation. We present a new methodology for studying human interaction to inform the design of interactive systems. In our digital ethnography we study a selection of YouTube videos and use Kendon's theory of F-formations to catalogue a set of spatial patterns created between cooks, kitchen spaces and cameras that influence the social aspects of cooking together. A new F-formation specific to this domain is identified and used to suggest design opportunities for a digitally enhanced kitchen space for sharing the social experience of "cooking together" for people living in different homes.

Keywords

Digital ethnography, collaborative cooking

ACM Classification Keywords

H.5.m. [Information interfaces and presentation (e.g., HCI)]: Miscellaneous;

General Terms

Human Factors.

Copyright is held by the author/owner(s).
CHI'12, May 5–10, 2012, Austin, Texas, USA.
ACM 978-1-4503-1016-1/12/05.

Specific Activities
Paay *et al.* 2012


Analyzing User-Generated YouTube Videos to Understand Touchscreen Use by People with Motor Impairments

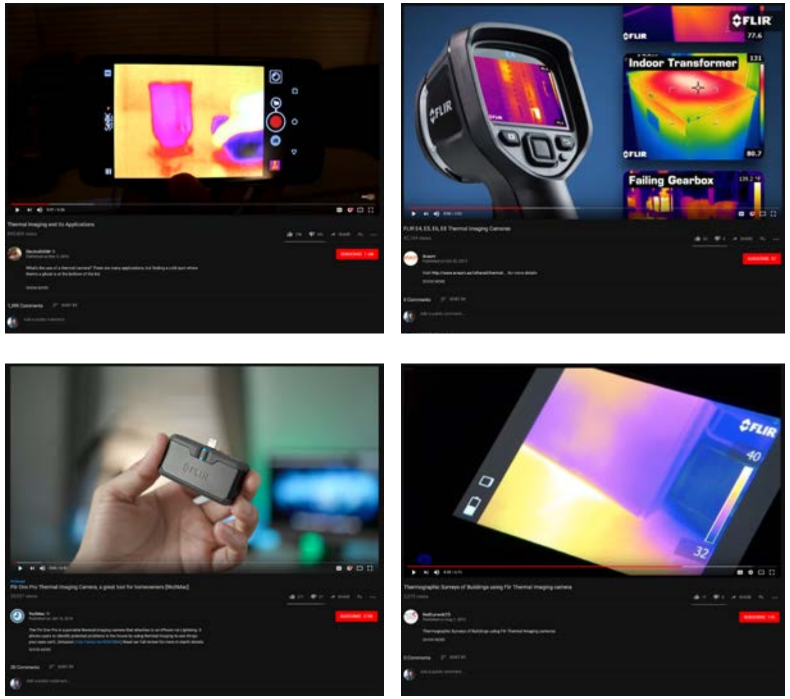
Lisa Anthony, UMBC Information Systems, 1000 Hilltop Circle, Baltimore MD 21250 USA, lanthony@umbc.edu

YooJin Kim, College of Information Studies, University of Maryland, College Park MD 20742 USA, ykim0710@umd.edu

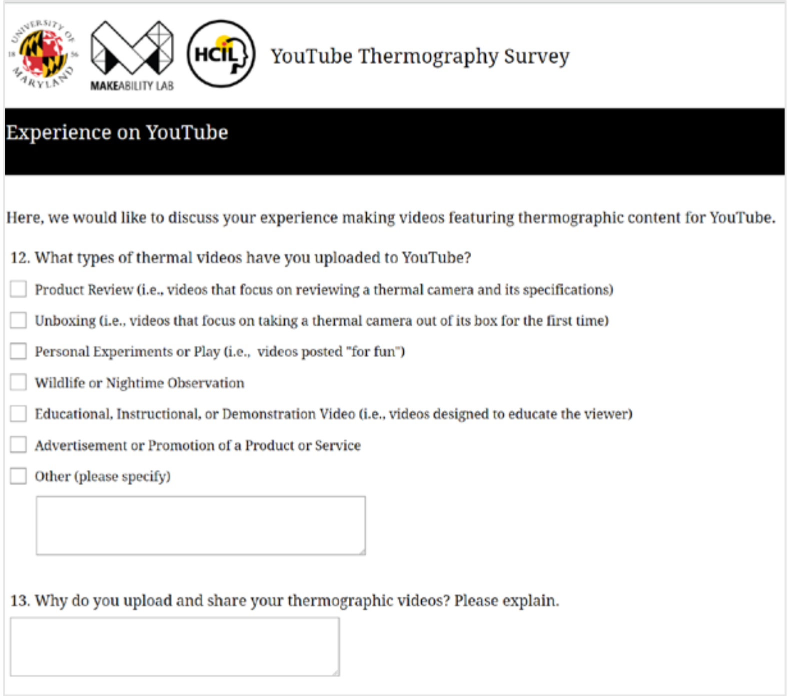
Leah Findlater, College of Information Studies, University of Maryland, College Park MD 20742 USA, leahkf@umd.edu

Specific Populations
Anthony *et al.* 2013

STUDY METHOD: TWO-PART STUDY



Part One:
Dataset Generation &
Qualitative Coding


YouTube Thermography Survey

MAKEABILITY LAB

Experience on YouTube

Here, we would like to discuss your experience making videos featuring thermographic content for YouTube.

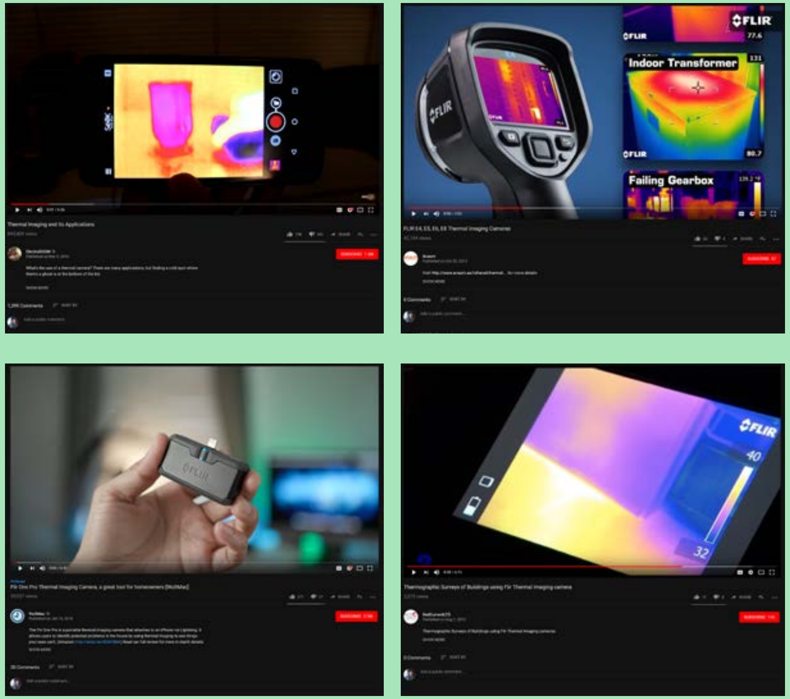
12. What types of thermal videos have you uploaded to YouTube?

- [ ] Product Review (i.e., videos that focus on reviewing a thermal camera and its specifications)
- [ ] Unboxing (i.e., videos that focus on taking a thermal camera out of its box for the first time)
- [ ] Personal Experiments or Play (i.e., videos posted "for fun")
- [ ] Wildlife or Nightime Observation
- [ ] Educational, Instructional, or Demonstration Video (i.e., videos designed to educate the viewer)
- [ ] Advertisement or Promotion of a Product or Service
- [ ] Other (please specify)

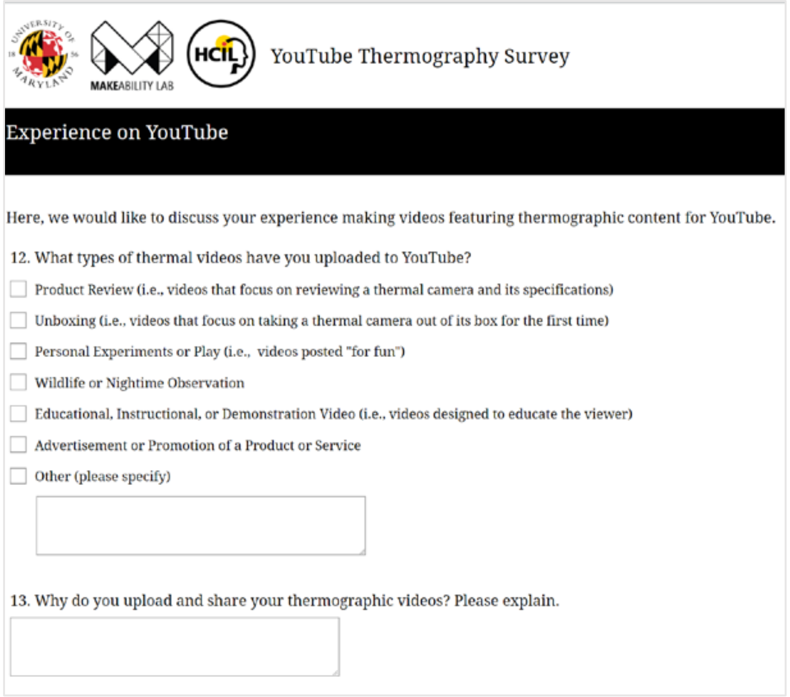
13. Why do you upload and share your thermographic videos? Please explain.

Part Two:
Online Survey of
Content Creators

Study Method: Two-Part Study



Part One:
Dataset Generation & Qualitative Coding



YouTube Thermography Survey

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HCIL

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- [ ] Other (please specify)

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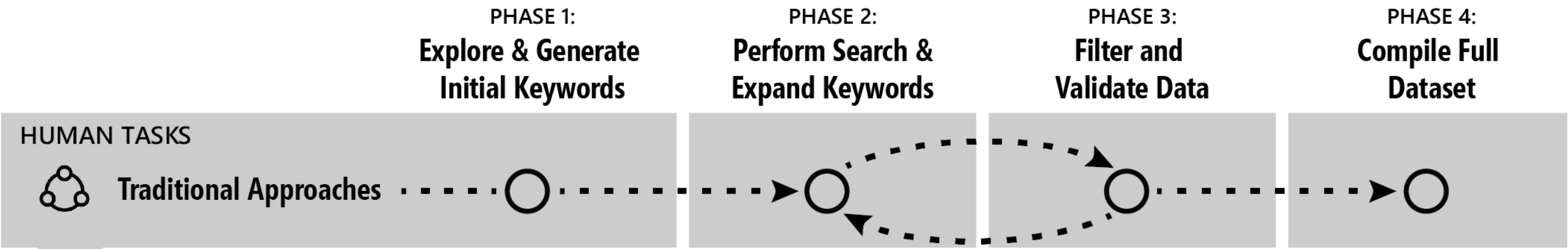
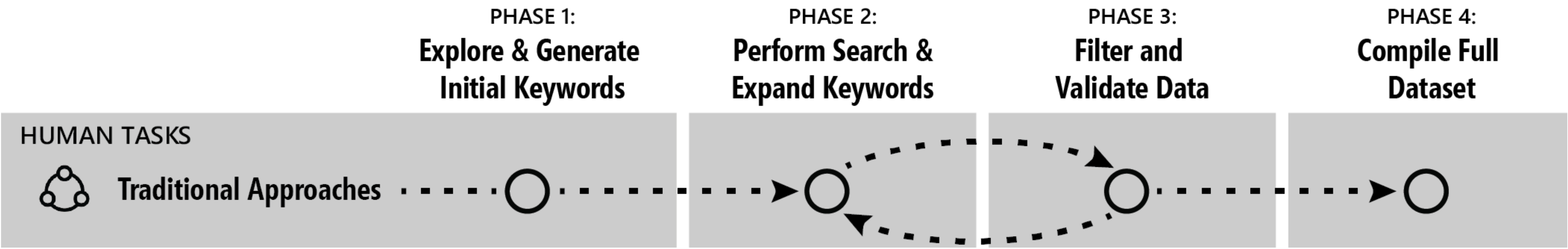
Part Two:
Online Survey of Content Creators

Study Method: Dataset Generation



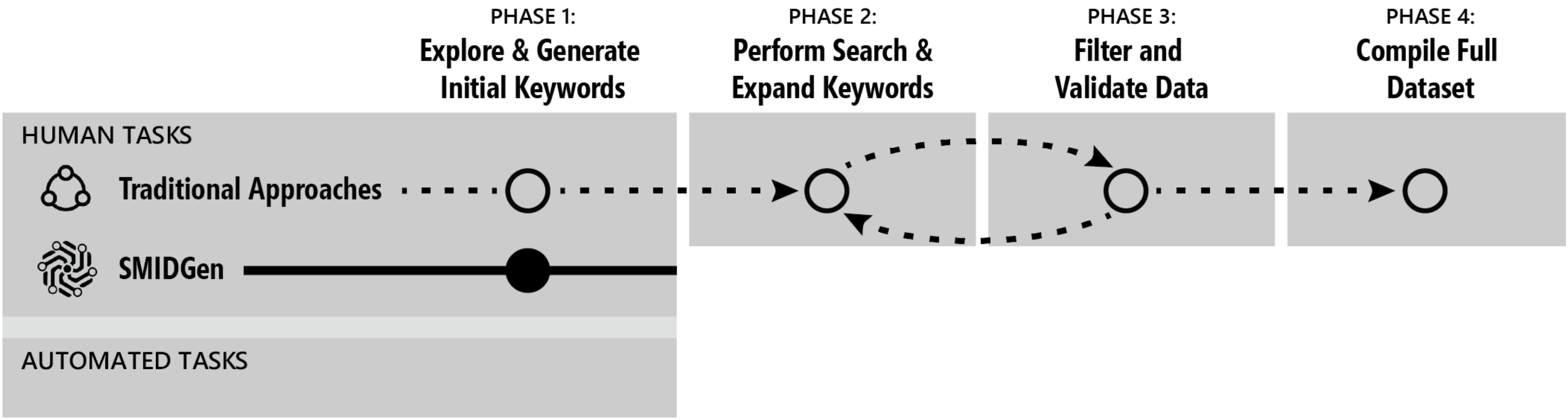
Study Method: Dataset Generation



Problem:

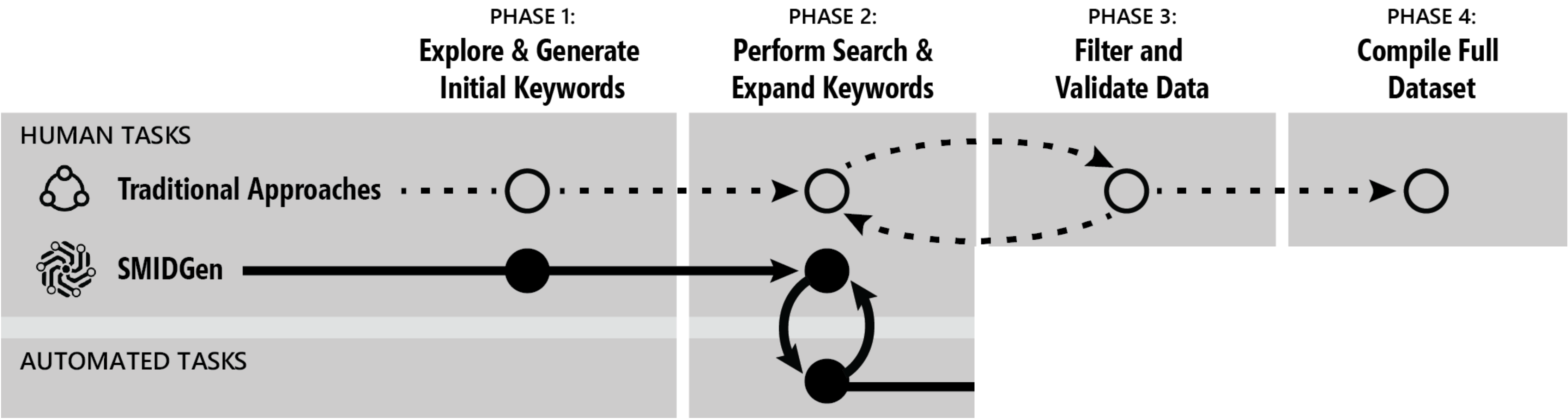
A search for "Thermal Camera" in July of 2017 resulted in over 1 million videos since 2005 compared to the 169 videos that resulted from "Cooking Together" in November of 2010.

STUDY METHOD: DATASET GENERATION



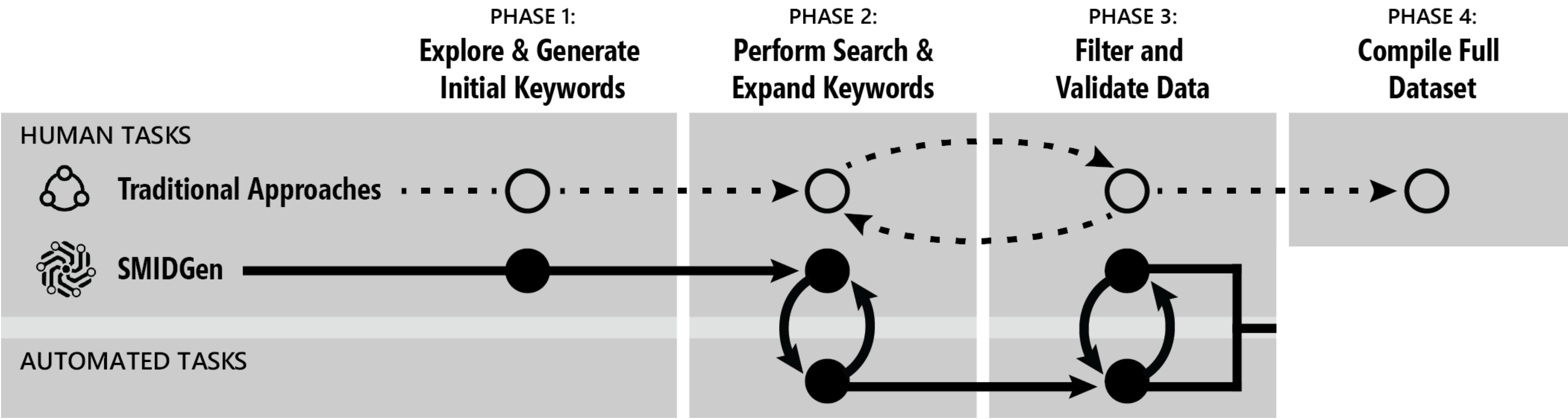
Phase 1: Explore videos on YouTube and generate initial keyword list.

STUDY METHOD: DATASET GENERATION



Phase 2: Perform searches. Then, apply Kullback-Leibler Divergence (KLD) and Word Co-Occurrence query expansion methods to generate new terms.

STUDY METHOD: DATASET GENERATION



Phase 3: Label a subset of data to train machine learning classifiers for filtering, then infer document labels on unseen videos.

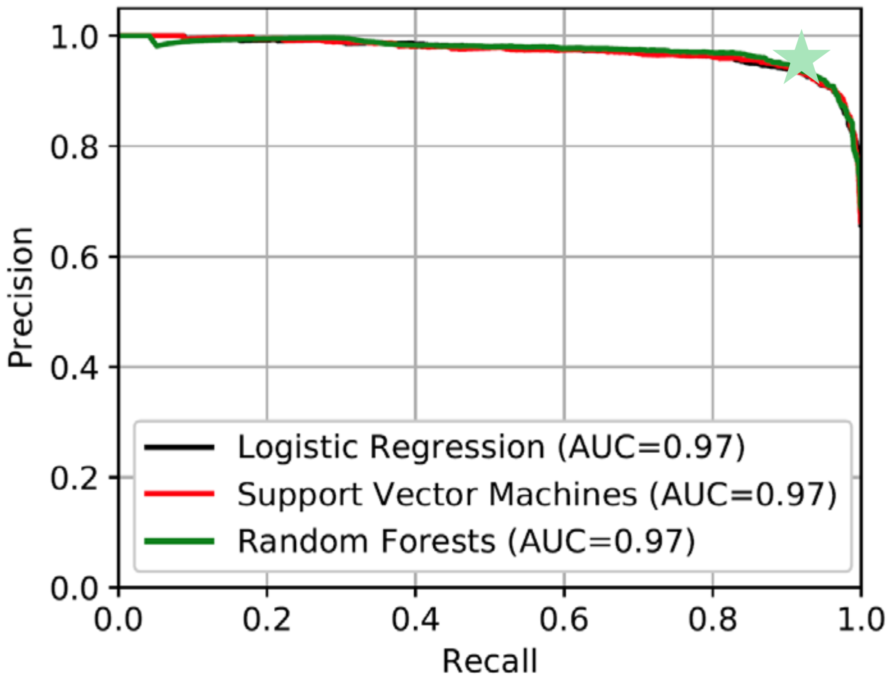
STUDY METHOD: DATASET GENERATION

Step	Terms
Step 1: Initial Keywords	infrared, lepton, thermal, thermal camera, thermal image, thermal imaging, thermography
Step 2: Expanded Keywords	breast thermography, flir lepton, flir one, flir thermal, imaging camera, infrared camera, infrared thermography, night vision, seek thermal, thermal imager
Step 3: Iterated Codebook	everyday use, product review, news coverage, unboxing, professional demo, advertisement, off topic

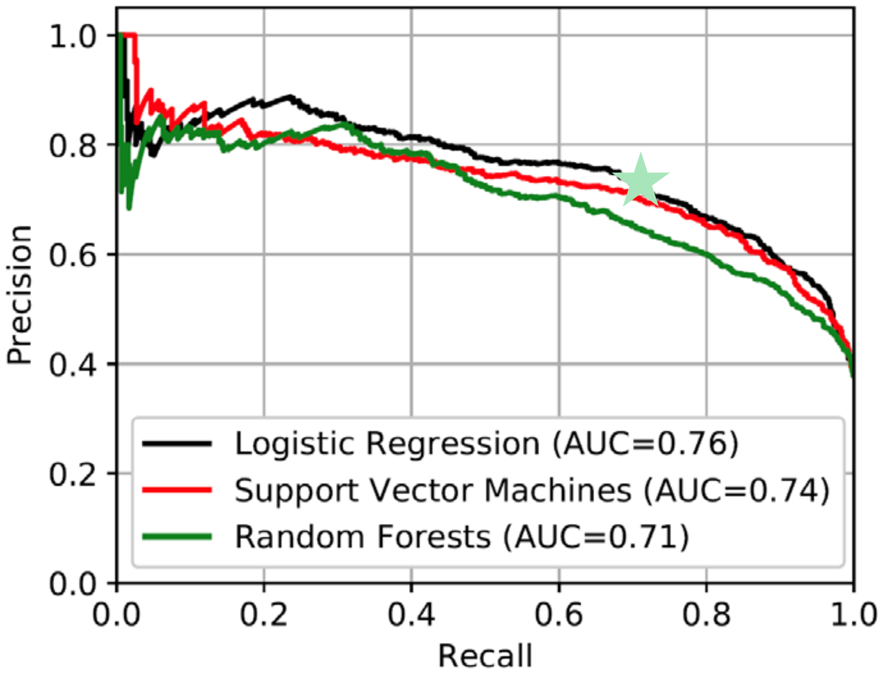
Average IRR across codes in Step 3 was 0.69 (SD=0.09)

Study Method: Dataset Generation

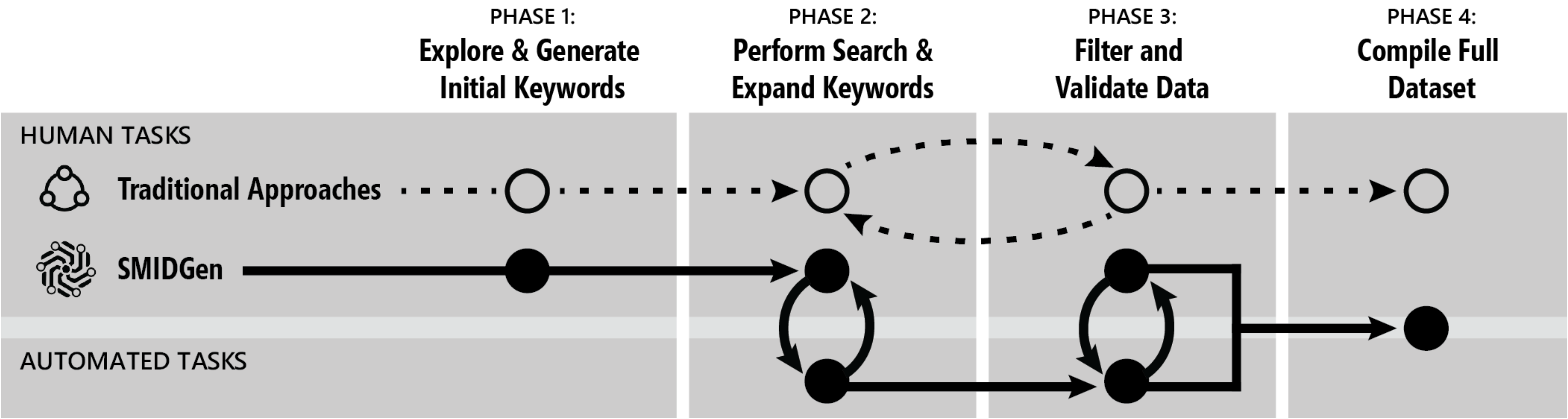
Relevance Classifier:
Thermography



Topical Classifier:
Everyday Use



STUDY METHOD: DATASET GENERATION



Phase 4: Randomly sample from resulting dataset.

Study Method: Dataset Generation

Topic Codes	Sub-Topic Codes
Content Areas (*N*=10)	Building and Urban Environments, Health and Wellness, Paranormal Investigations, Electronics and Software Projects, Recreational Outdoor Activities and Agriculture, Informal Exploration, Pollution Activism, Vehicles, Research, Security and Emergency Services
Misconceptions (*N*=6)	See Through Objects, Measure Air Temperature, Measure Gases, Faux Filters, Faux Thermal Imagers, Camera Operation Issues
Comments Containing Q/A (*N*=4)	Content Questions, Technical Specifications, Follow-up Request, Other

Average IRR of 0.75 (SD=0.27)

STUDY FINDINGS: QUALITATIVE CODING

Categories	Dataset (N=675)	Average Duration (SD)	Median Views	Contains Misconceptions	Q&A in Comment
Informal Exploration	46.5% (314)	2.28 (5.11)	507	9.8% (31/314)	27.7% (87/314)
Outdoor Recreation & Agriculture	16.1% (109)	3.24 (7.50)	807	0.9% (38/109)	34.8% (38/109)
Electronic or Software Project	11.9% (80)	3.03 (4.70)	368	1.2% (1/80)	28.7% (23/80)
Buildings and Urban Observations	11.1% (75)	3.06 (4.11)	351	4.0% (3/75)	24.0% (18/75)
Vehicles	6.5% (44)	1.90 (2.48)	822	0.0% (0/44)	27.2% (12/44)
Paranormal Investigations	2.8% (19)	4.30 (4.25)	2327	10.5% (2/19)	63.1% (12/19)
Emergency Applications	2.1% (14)	1.09 (1.05)	637	7.14% (1/14)	28.5% (4/14)
Health and Wellness	1.8% (12)	5.19 (7.49)	2116	0.0% (0/12)	0.3% (4/12)
Research	0.9% (6)	1.02 (0.80)	385	0.0% (0/6)	16.6 (1/6)
Pollution Activism	0.3% (2)	0.34 (0.03)	103	0.0% (0/2)	0.0% (0/2)

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Electronic or Software Project	11.9% (80)	3.03 (4.70)	368	1.2% (1/80)	28.7% (23/80)
Buildings and Urban Observations	11.1% (75)	3.06 (4.11)	351	4.0% (3/75)	24.0% (18/75)
Vehicles	6.5% (44)	1.90 (2.48)	822	0.0% (0/44)	27.2% (12/44)
Paranormal Investigations	2.8% (19)	4.30 (4.25)	2327	10.5% (2/19)	63.1% (12/19)
Emergency Applications	2.1% (14)	1.09 (1.05)	637	7.14% (1/14)	28.5% (4/14)
Health and Wellness	1.8% (12)	5.19 (7.49)	2116	0.0% (0/12)	0.3% (4/12)
Research	0.9% (6)	1.02 (0.80)	385	0.0% (0/6)	16.6 (1/6)
Pollution Activism	0.3% (2)	0.34 (0.03)	103	0.0% (0/2)	0.0% (0/2)

STUDY FINDINGS: QUALITATIVE CODING

Categories	Dataset (N=675)	Average Duration (SD)	Median Views	Contains Misconceptions	Q&A in Comment
Informal Exploration	46.5% (314)	2.28 (5.11)	507	9.8% (31/314)	27.7% (87/314)
Outdoor Recreation & Agriculture	16.1% (109)	3.24 (7.50)	807	0.9% (38/109)	34.8% (38/109)
Electronic or Software Project	11.9% (80)	3.03 (4.70)	368	1.2% (1/80)	28.7% (23/80)
Buildings and Urban Observations	11.1% (75)	3.06 (4.11)	351	4.0% (3/75)	24.0% (18/75)
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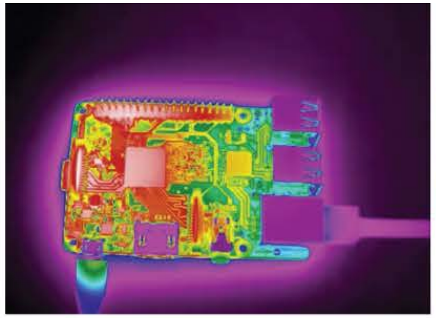
Pollution Activism	0.3% (2)	0.34 (0.03)	103	0.0% (0/2)	0.0% (0/2)

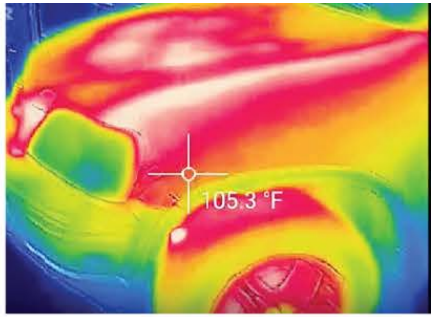
Study Findings: Qualitative Coding


Informal Exploration (46.5%)


Outdoor Recreation & Agriculture (16.1%)

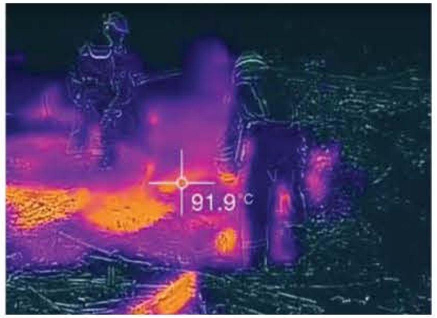
Buildings & Urban Environments (11.1%)


Small Electronics (11.9%)

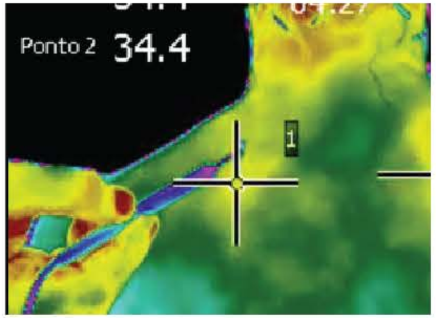


Vehicles (6.5%)

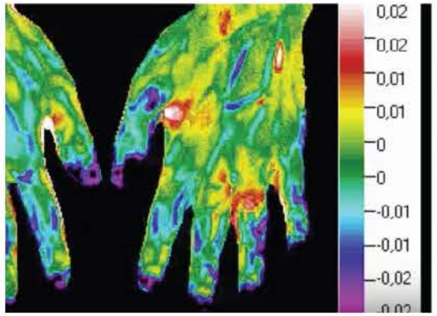
Paranormal Investigations (2.8%)



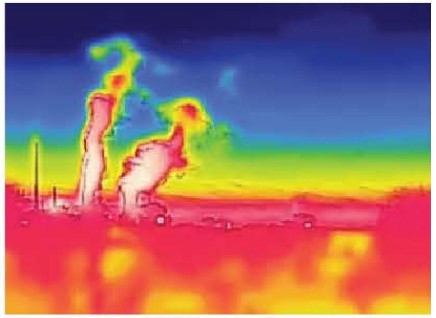
Emergency Applications (2.1%)



Health and Wellness (1.8%)



Research (0.9%)

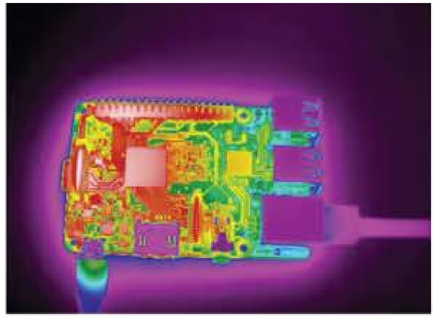

Pollution Activism (0.3%)

Study Findings: Qualitative Coding

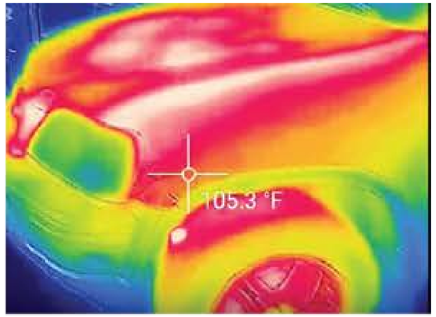
Informal Exploration (46.5%)

Outdoor Recreation & Agriculture (16.1%)

Buildings & Urban Environments (11.1%)

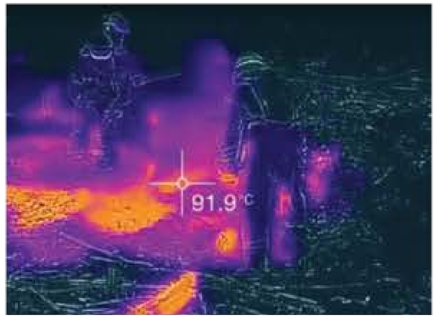


Small Electronics (11.9%)

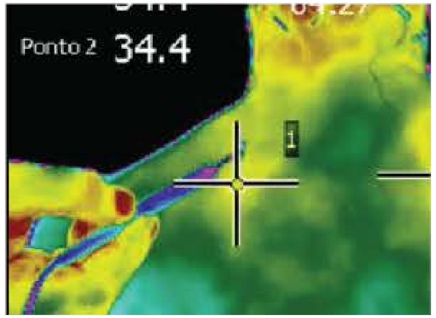


Vehicles (6.5%)

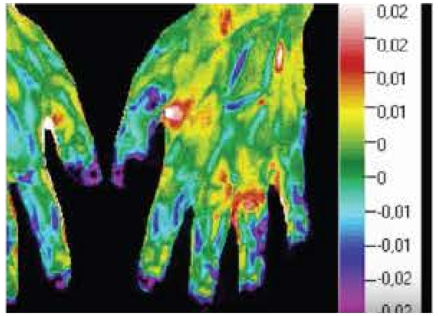
Paranormal Investigations (2.8%)



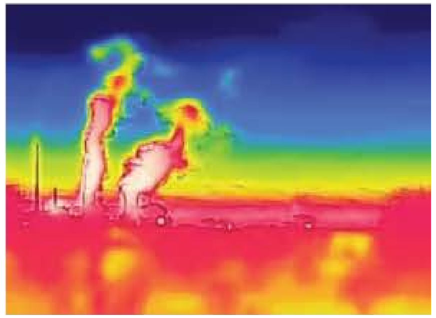
Emergency Applications (2.1%)



Health and Wellness (1.8%)



Research (0.9%)



Pollution Activism (0.3%)

“Can a Thermal Camera See Through water?”

“I’m going to dip my hand down into the aquarium, right into the water, and let’s see what happens. I’m going to **calibrate the camera first**.

(Dips hand in aquarium.)

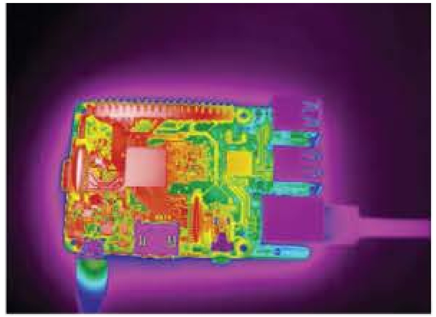
Yeah the surface of the water really reflects the heat away. But we can actually see my hand is heating the very surface of the water. [...] So yeah, the thermal camera doesn’t see through water very well, **but it is sensitive enough that you can** actually see my hand warming up the water. **Pretty cool**.”

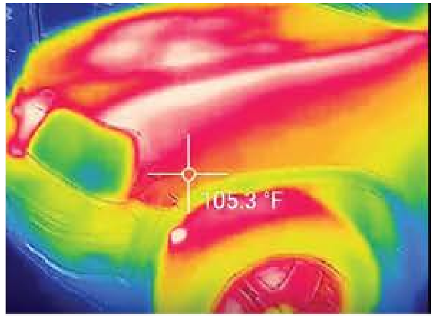
STUDY FINDINGS: QUALITATIVE CODING


Informal Exploration (46.5%)


Outdoor Recreation & Agriculture (16.1%)

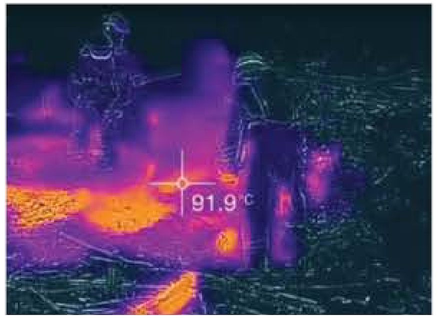
Buildings & Urban Environments (11.1%)


Small Electronics (11.9%)

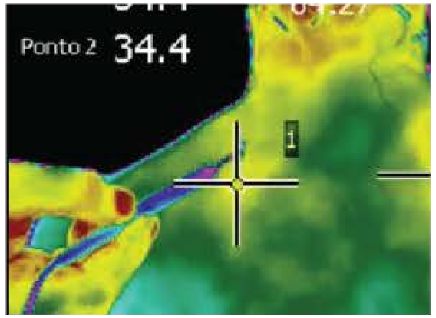


Vehicles (6.5%)

Paranormal Investigations (2.8%)



Emergency Applications (2.1%)



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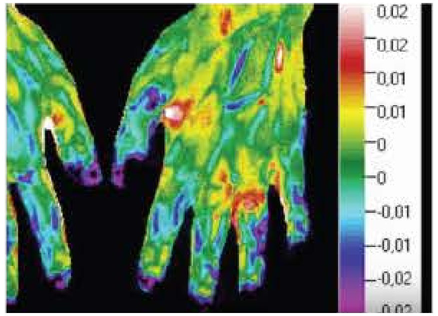
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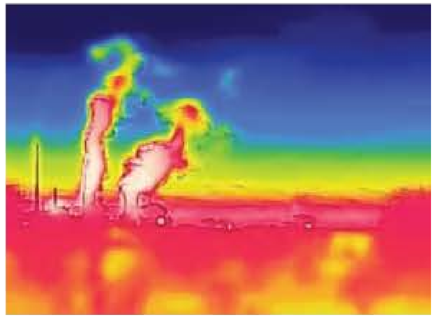

Pollution Activism (0.3%)

“DIY Home Energy Audit with an IR Camera”

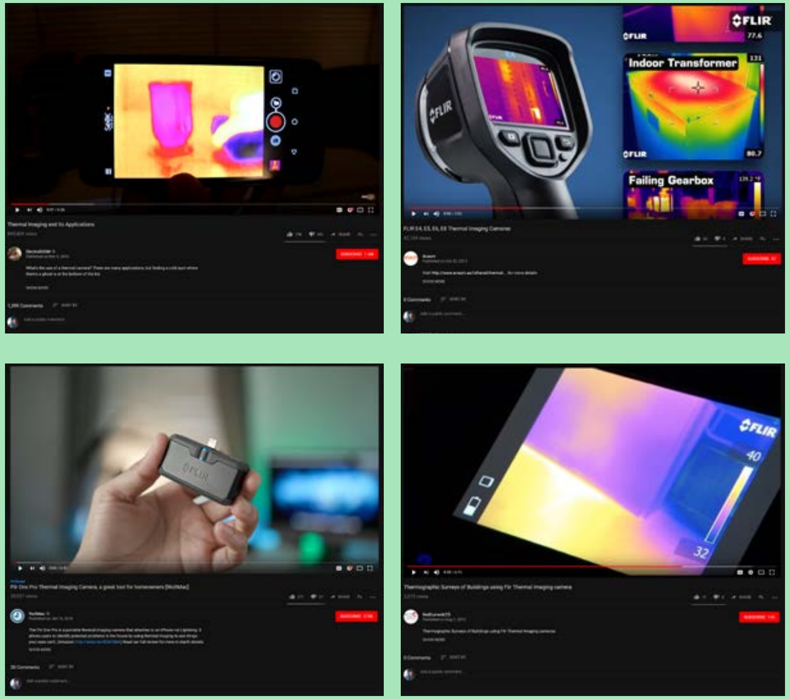
“Now, something of great interest…and these are the types of things that are really cool to discover when you’re doing these types of audits.

Here in the ceiling, we can see areas that are significantly warmer than the areas around them. **Sometimes this is bleed-through from the heat coming from the windows**.

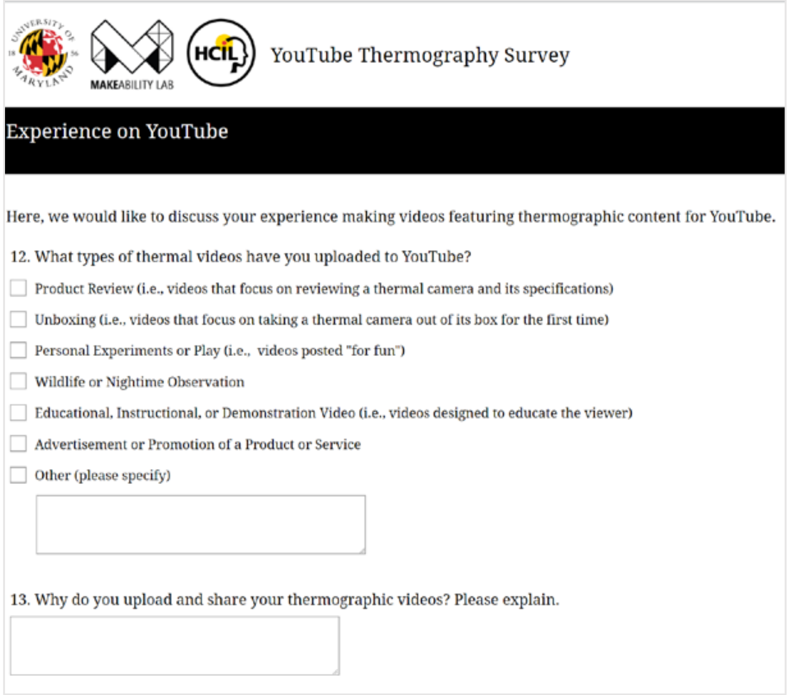
(left corner)

This, however, indicates that the insulation does not cover all the way to the corner of the house. So, we’re missing some insulation here.”

Study Method: Two-Part Study



Part One:
Dataset Generation & Qualitative Coding


YouTube Thermography Survey

MAKEABILITY LAB

Experience on YouTube

Here, we would like to discuss your experience making videos featuring thermographic content for YouTube.

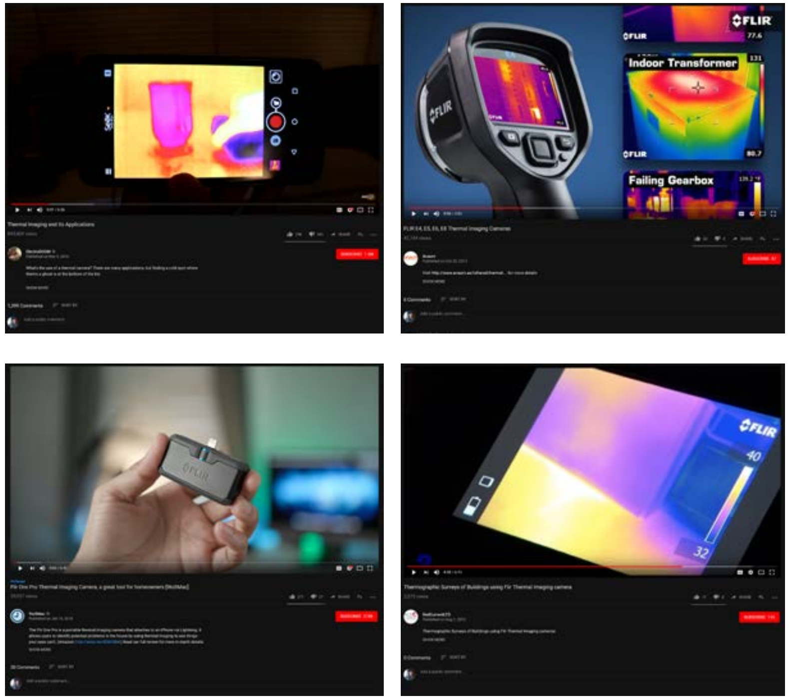
12. What types of thermal videos have you uploaded to YouTube?

- [ ] Product Review (i.e., videos that focus on reviewing a thermal camera and its specifications)
- [ ] Unboxing (i.e., videos that focus on taking a thermal camera out of its box for the first time)
- [ ] Personal Experiments or Play (i.e., videos posted "for fun")
- [ ] Wildlife or Nightime Observation
- [ ] Educational, Instructional, or Demonstration Video (i.e., videos designed to educate the viewer)
- [ ] Advertisement or Promotion of a Product or Service
- [ ] Other (please specify)

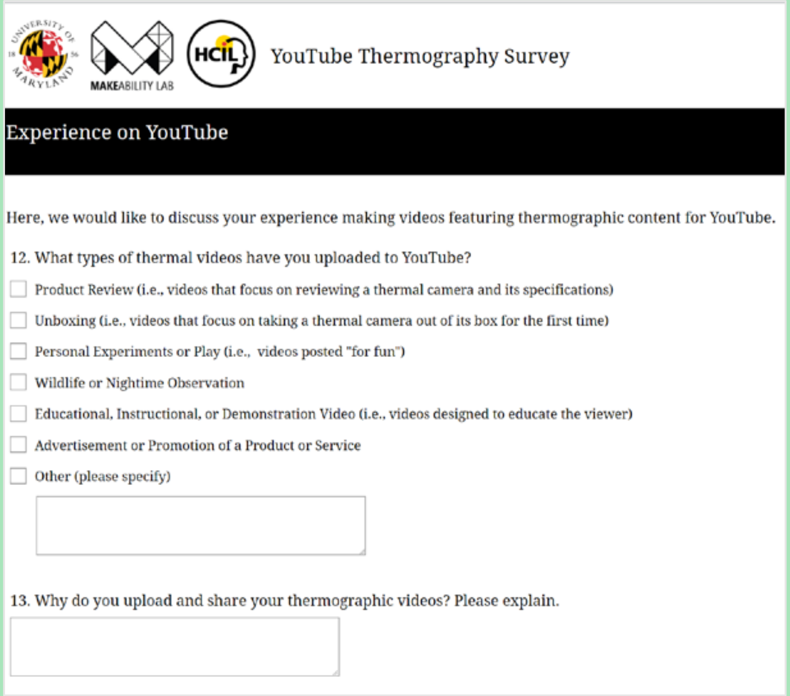
13. Why do you upload and share your thermographic videos? Please explain.

Part Two:
Online Survey of Content Creators

Study Method: Two-Part Study



Part One:
Dataset Generation & Qualitative Coding



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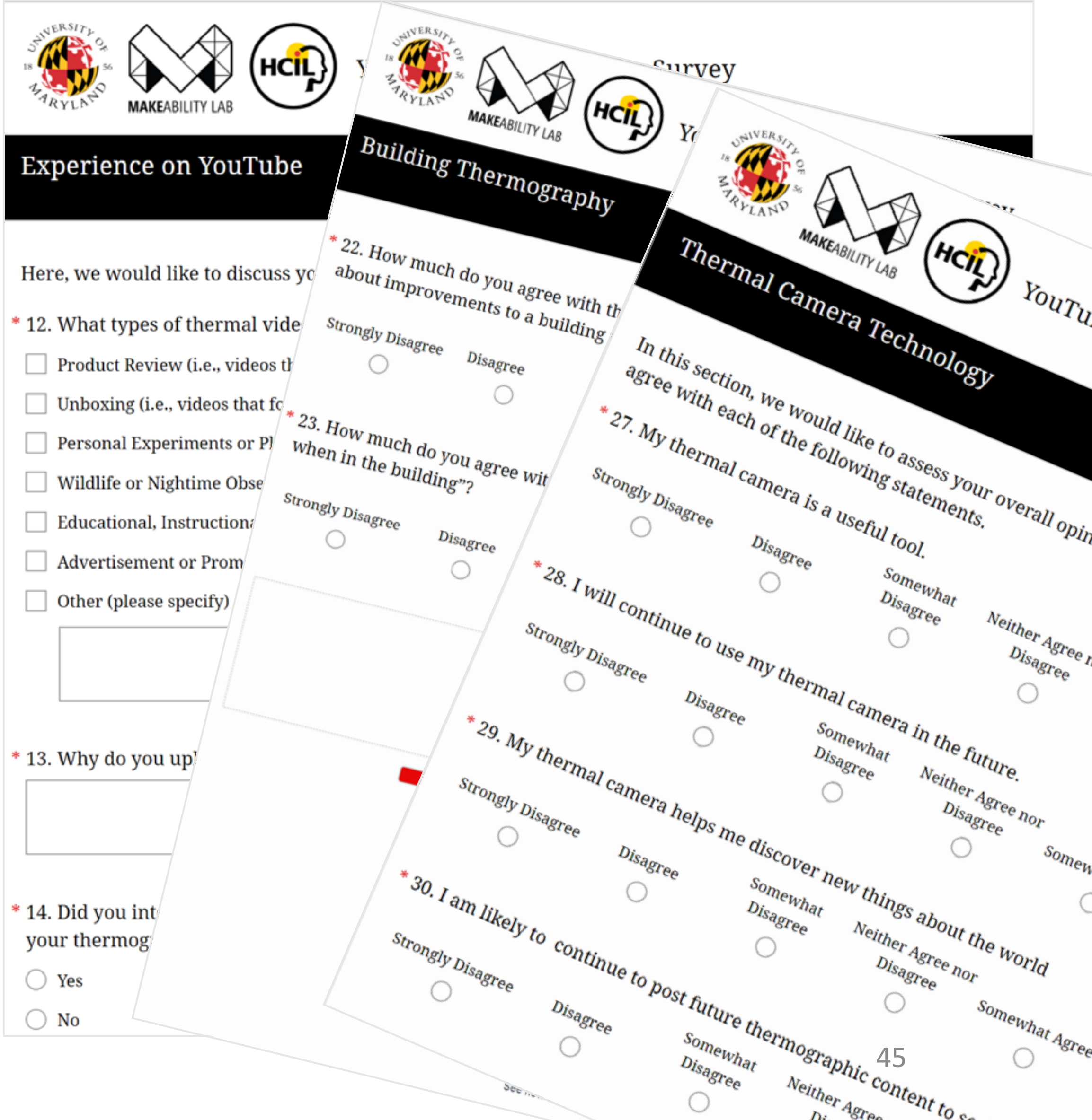
- ☐ Other (please specify)

13. Why do you upload and share your thermographic videos? Please explain.

Part Two:
Online Survey of Content Creators

STUDY METHOD: ONLINE SURVEY

- Content creators with videos in our n=1000 random sample were sent requests to participate
- 79 content creators responded (7.7% response rate)
- 48 respondents identified as non-professionals (61%)



72%

(*N*=35) use thermal cameras to perform DIY Energy Audits

They report performing inspections of:

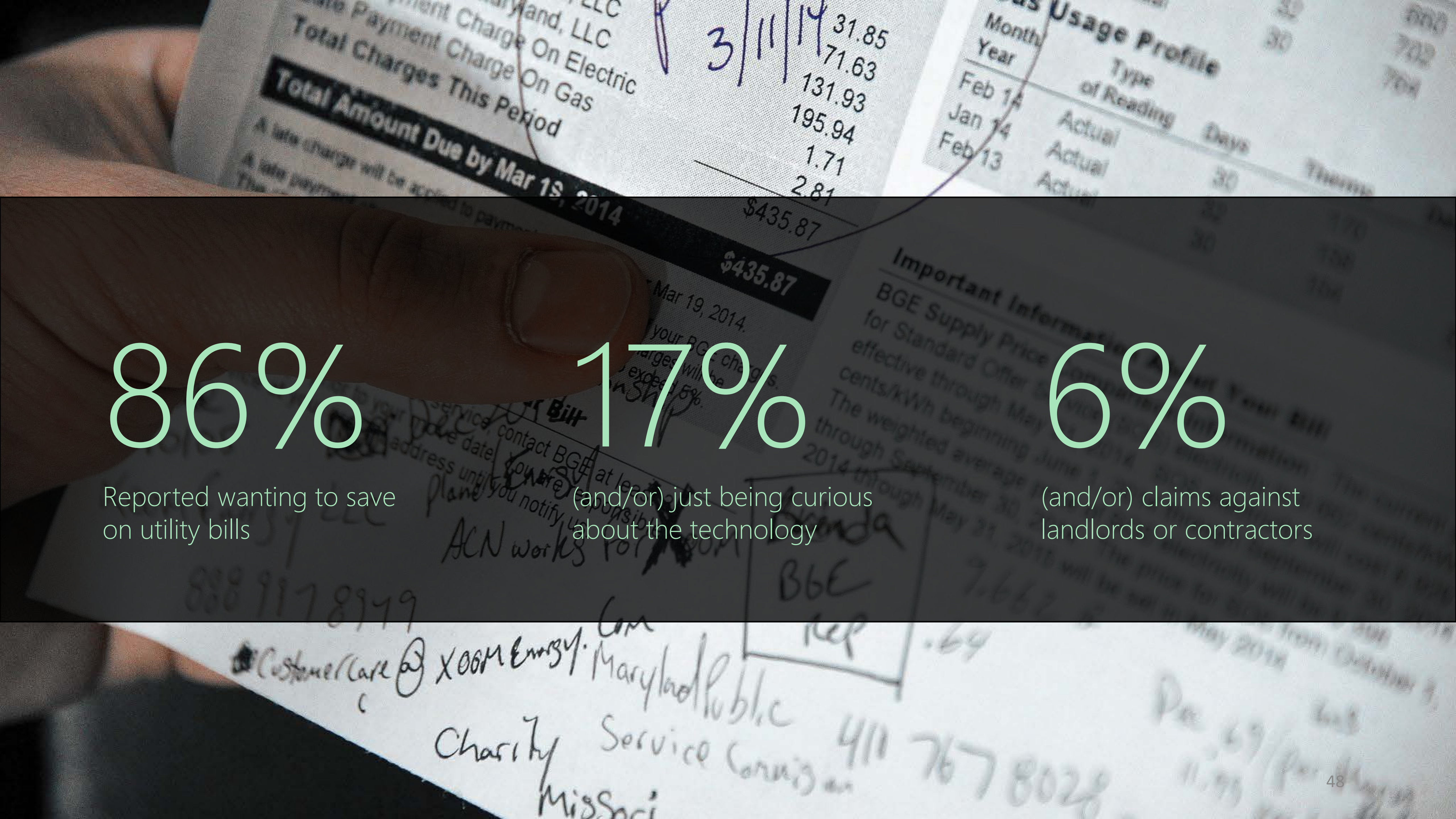
- Insulation
- Air Leakage
- Electrical
- Moisture

86%

Audit single-family residential homes

But, also report auditing other types:

- Multi-family
- Commercial
- School & Universities
- Government Offices
- Community Buildings



86%

Reported wanting to save on utility bills

17%

(and/or) just being curious about the technology

6%

(and/or) claims against landlords or contractors

60%

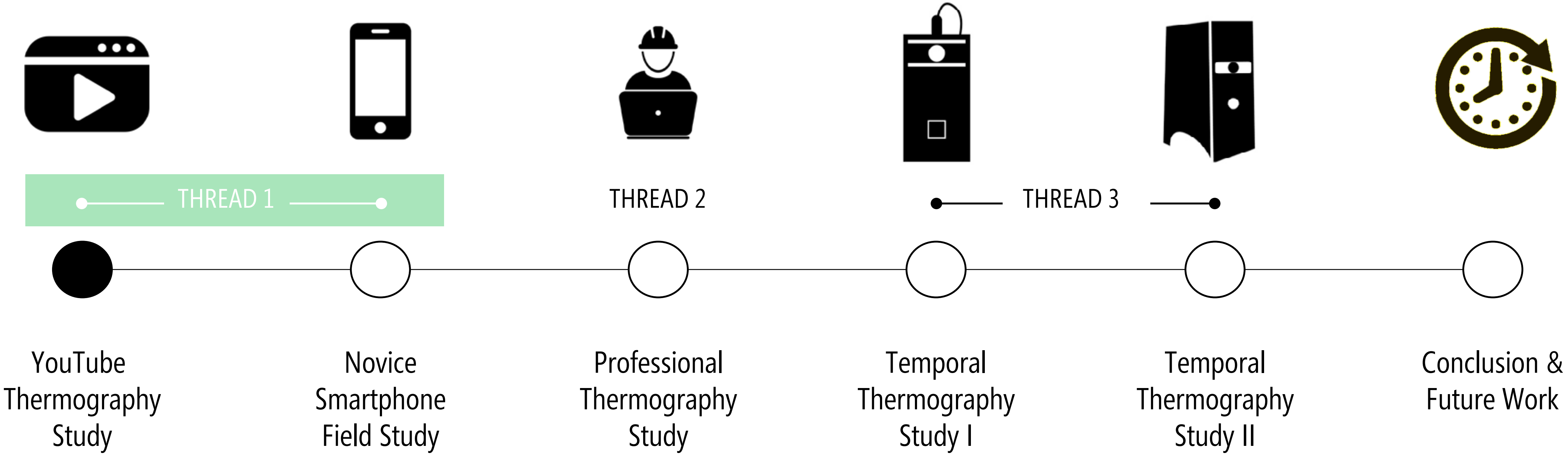
Reported investing in renovations or retrofits

Fewer (30%) engaged in new conservation behaviors.

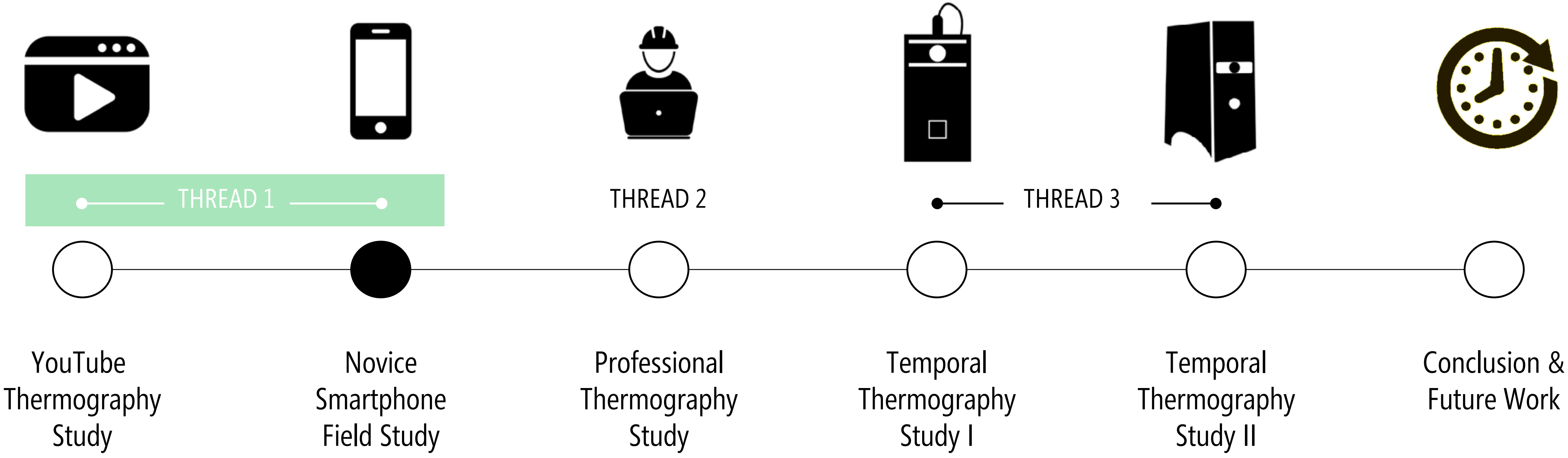
YOUTUBE STUDY: RESEARCH OUTCOMES

- **Characterizations of common thermal camera use** and adoption by novices users including building thermography
- Provides supporting evidence that suggests **DIY, thermographic energy audits positively impact residential energy efficiency**
- Provides 4 design recommendations including the importance of providing contextual relevant information and **leveraging social supports to promote technical understanding and proper use**.

DISSERTATION OVERVIEW



DISSERTATION OVERVIEW




FLIR
72.5°F

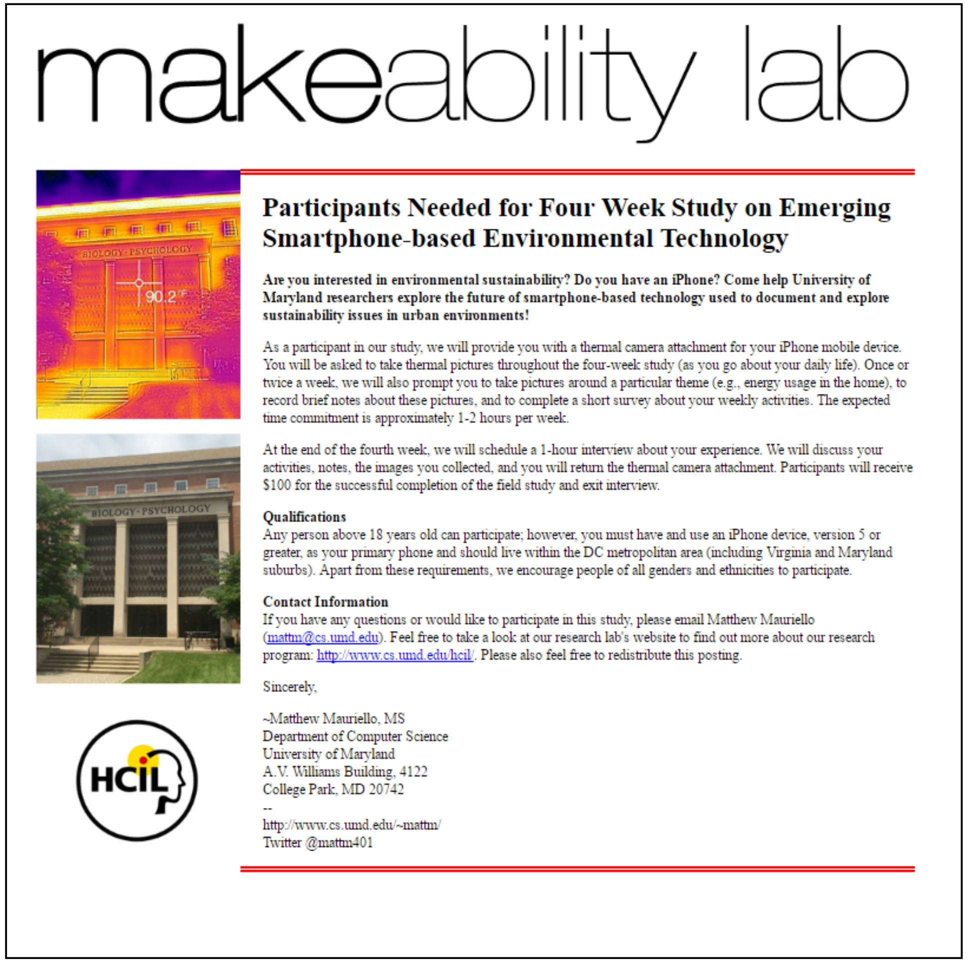
NOVICE SMARTPHONE FIELD STUDY: RESEARCH QUESTIONS

1 How might novice users of commercial thermal cameras assess the built environment?

2 What attributes of the built environment do they focus on, learn about, and what do they discover?

3 What challenges do they encounter and what benefits do they perceive?

Study Design: Recruitment


makeability lab

Participants Needed for Four Week Study on Emerging Smartphone-based Environmental Technology

Are you interested in environmental sustainability? Do you have an iPhone? Come help University of Maryland researchers explore the future of smartphone-based technology used to document and explore sustainability issues in urban environments!

As a participant in our study, we will provide you with a thermal camera attachment for your iPhone mobile device. You will be asked to take thermal pictures throughout the four-week study (as you go about your daily life). Once or twice a week, we will also prompt you to take pictures around a particular theme (e.g., energy usage in the home), to record brief notes about these pictures, and to complete a short survey about your weekly activities. The expected time commitment is approximately 1-2 hours per week.

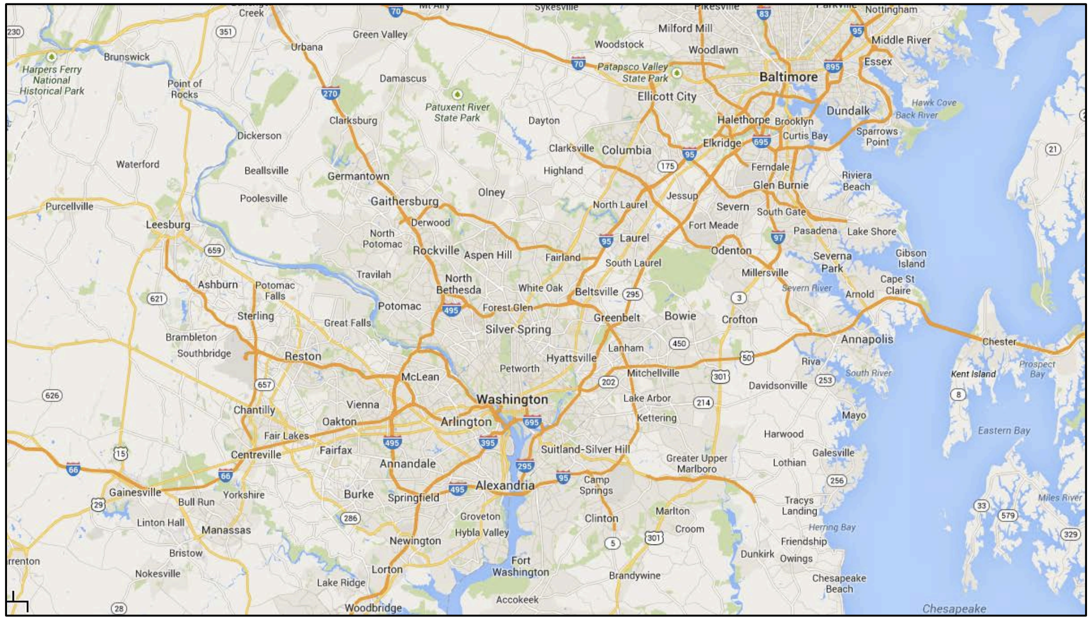
At the end of the fourth week, we will schedule a 1-hour interview about your experience. We will discuss your activities, notes, the images you collected, and you will return the thermal camera attachment. Participants will receive $100 for the successful completion of the field study and exit interview.

Qualifications
Any person above 18 years old can participate; however, you must have and use an iPhone device, version 5 or greater, as your primary phone and should live within the DC metropolitan area (including Virginia and Maryland suburbs). Apart from these requirements, we encourage people of all genders and ethnicities to participate.

Contact Information
If you have any questions or would like to participate in this study, please email Matthew Mauriello (mattm@cs.umd.edu). Feel free to take a look at our research lab's website to find out more about our research program: http://www.cs.umd.edu/hcil/. Please also feel free to redistribute this posting.

Sincerely,

~Matthew Mauriello, MS
Department of Computer Science
University of Maryland
A.V. Williams Building, 4122
College Park, MD 20742
--
http://www.cs.umd.edu/~mattm/
Twitter @mattm401



We recruited local participants using listserv, community message boards, and word-of-mouth.

STUDY METHOD: PARTICIPANTS

10 Participants (5 Female)

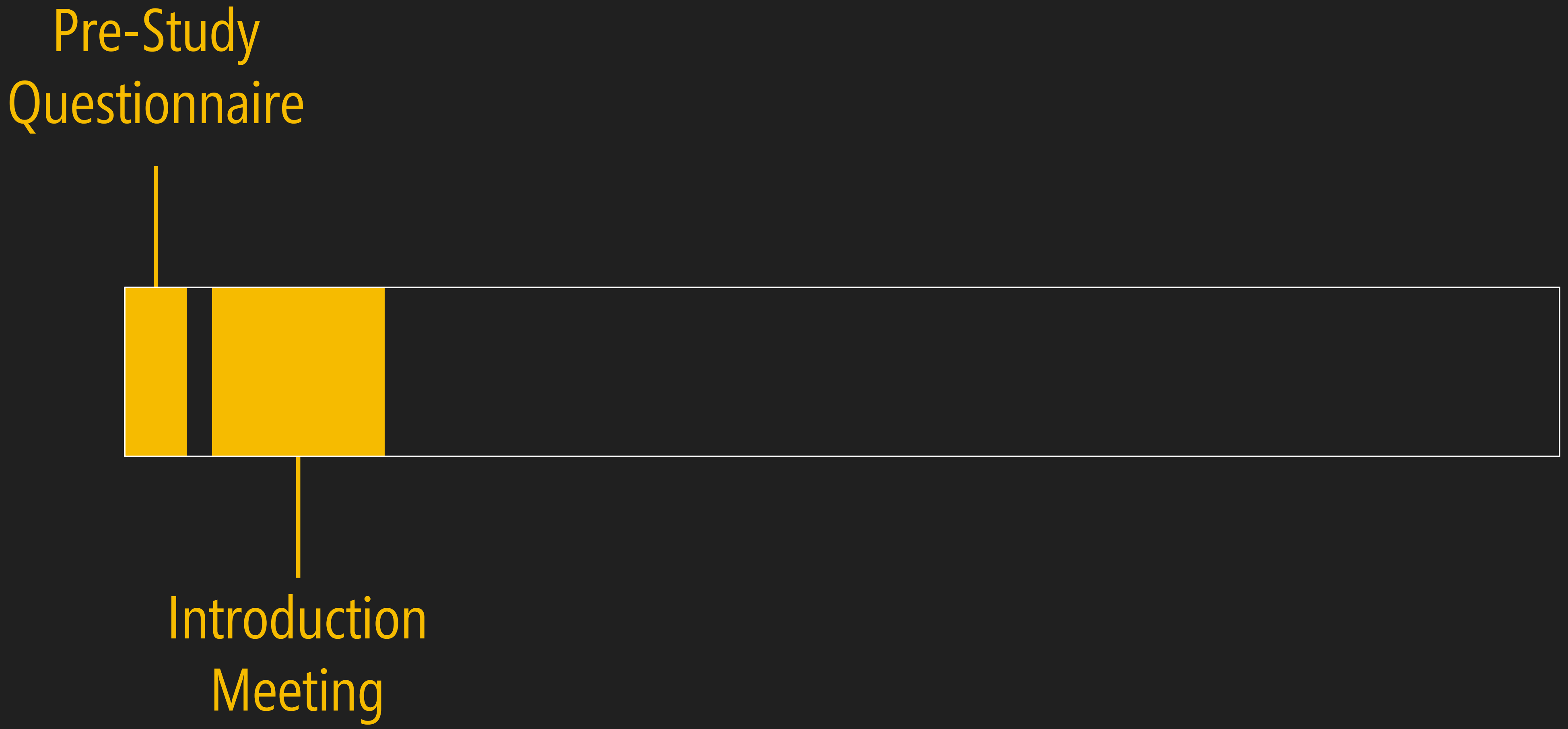
Avg. Age:	37.7 Years
Avg. Green:	6.7 (7pt Likert)

STUDY METHOD: FIELD STUDY PROCEDURE

Study Method: Field Study Procedure

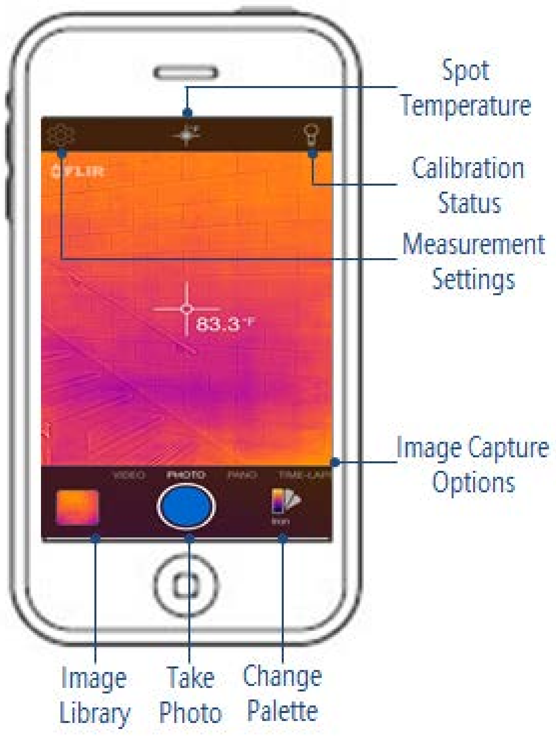
Pre-Study
Questionnaire

STUDY METHOD: FIELD STUDY PROCEDURE

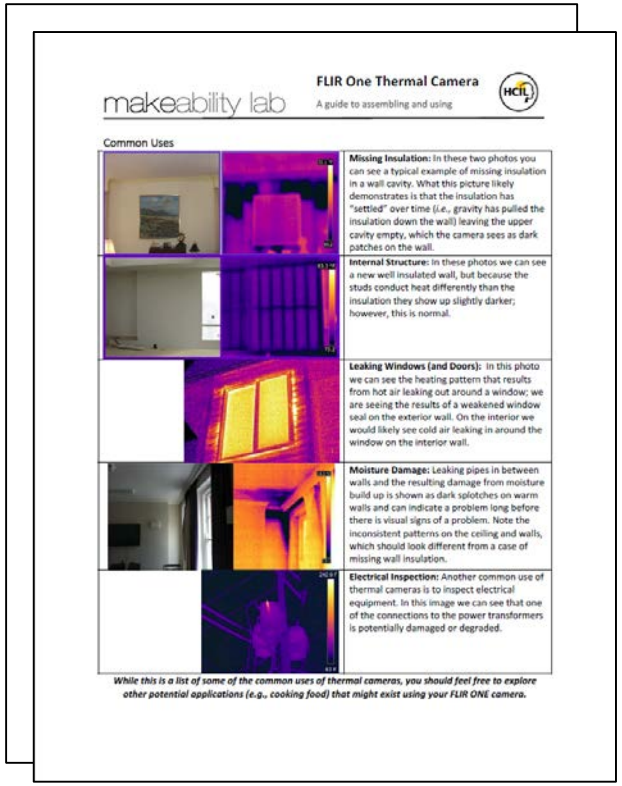



FLIR

STUDY METHOD: TRAINING



Hardware/Software Overview



makeability lab

FLIR One Thermal Camera

A guide to assembling and using

Common Uses

Missing Insulation: In these two photos you can see a typical example of missing insulation in a wall cavity. What this picture likely demonstrates is that the insulation has "settled" over time (*i.e.*, gravity has pulled the insulation down the wall) leaving the upper cavity empty, which the camera sees as dark patches on the wall.

Internal Structure: In these photos we can see a new well insulated wall, but because the studs conduct heat differently than the insulation they show up slightly darker; however, this is normal.

Leaking Windows (and Doors): In this photo we can see the heating pattern that results from hot air leaking out around a window; we are seeing the results of a weakened window seal on the exterior wall. On the interior we would likely see cold air leaking in around the window on the interior wall.

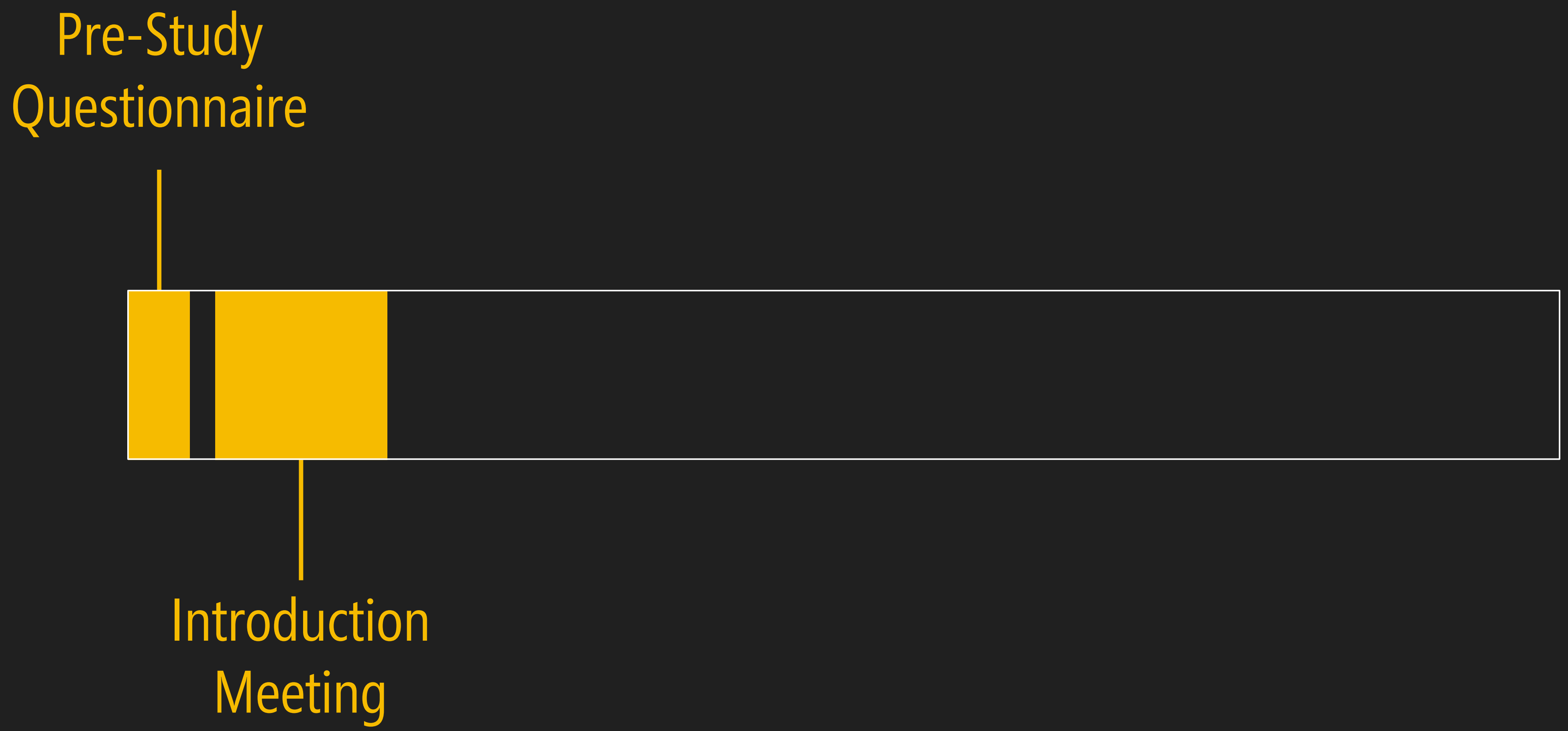
Moisture Damage: Leaking pipes in between walls and the resulting damage from moisture build up is shown as dark splotches on warm walls and can indicate a problem long before there is visual signs of a problem. Note the inconsistent patterns on the ceiling and walls, which should look different from a case of missing wall insulation.

Electrical Inspection: Another common use of thermal cameras is to inspect electrical equipment. In this image we can see that one of the connections to the power transformers is potentially damaged or degraded.

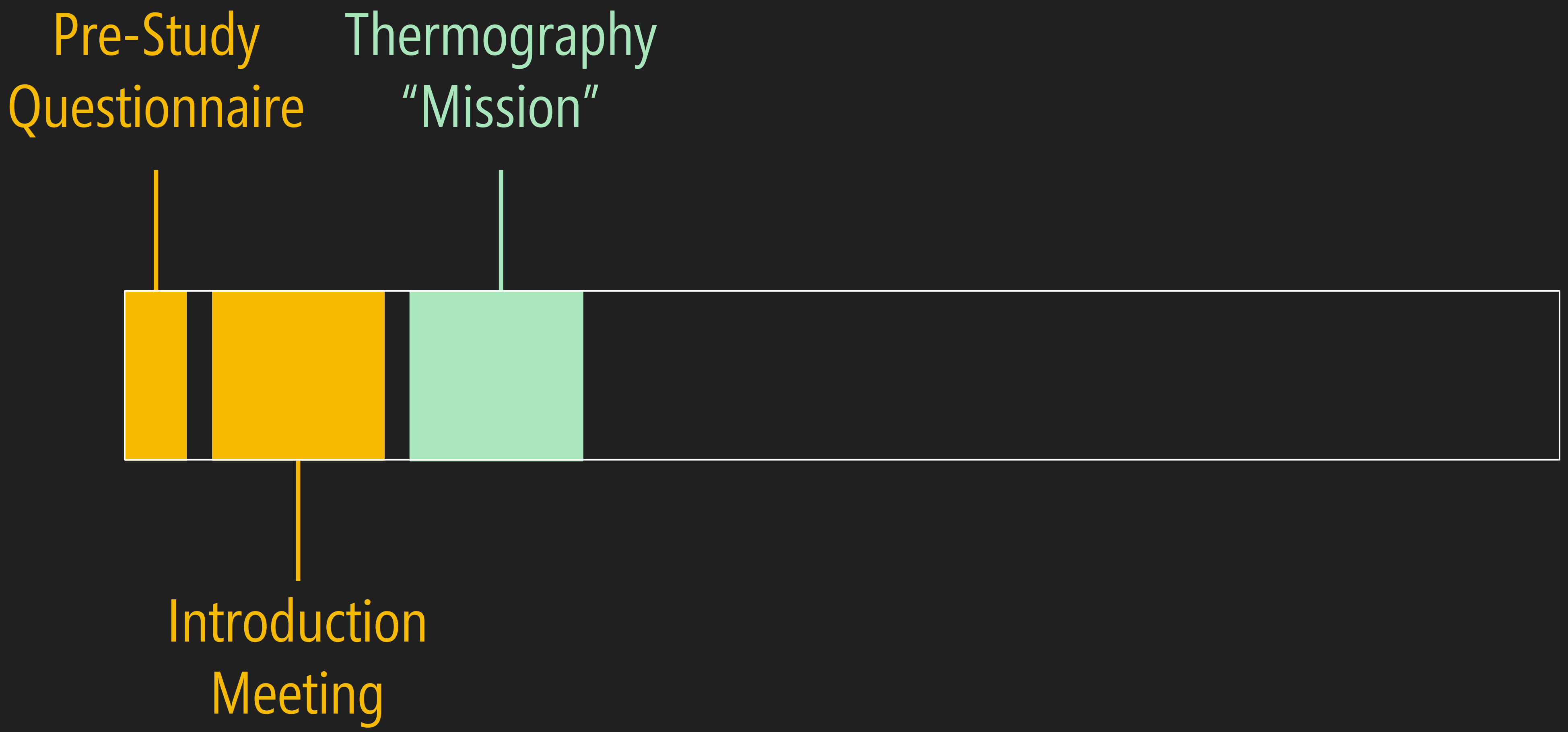
While this is a list of some of the common uses of thermal cameras, you should feel free to explore other potential applications (e.g., cooking food) that might exist using your FLIR ONE camera.

4-Page Thermographic Inspection Guide

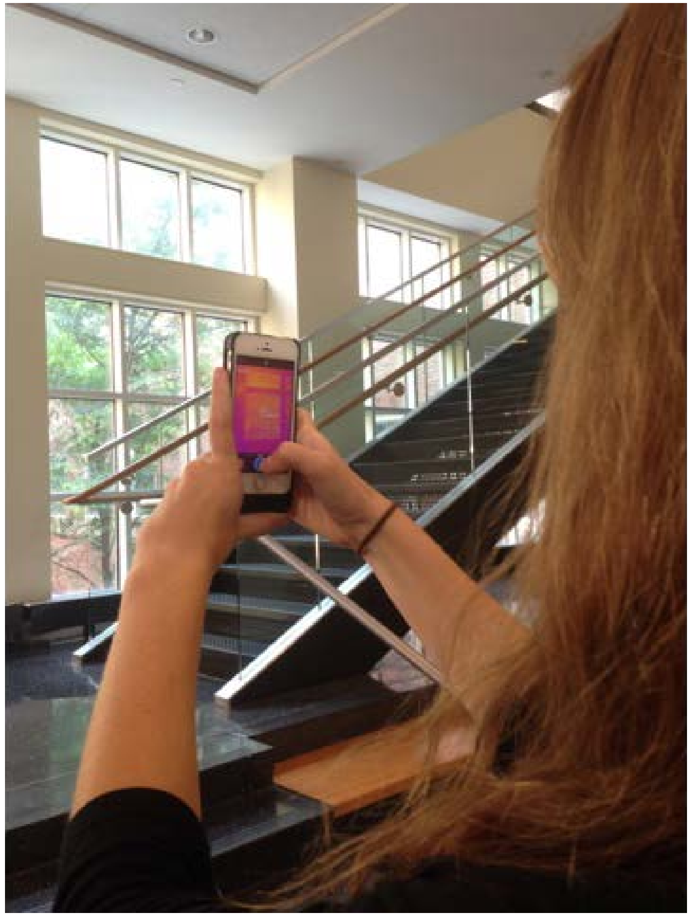
Study Method: Field Study Procedure



Study Method: Field Study Procedure

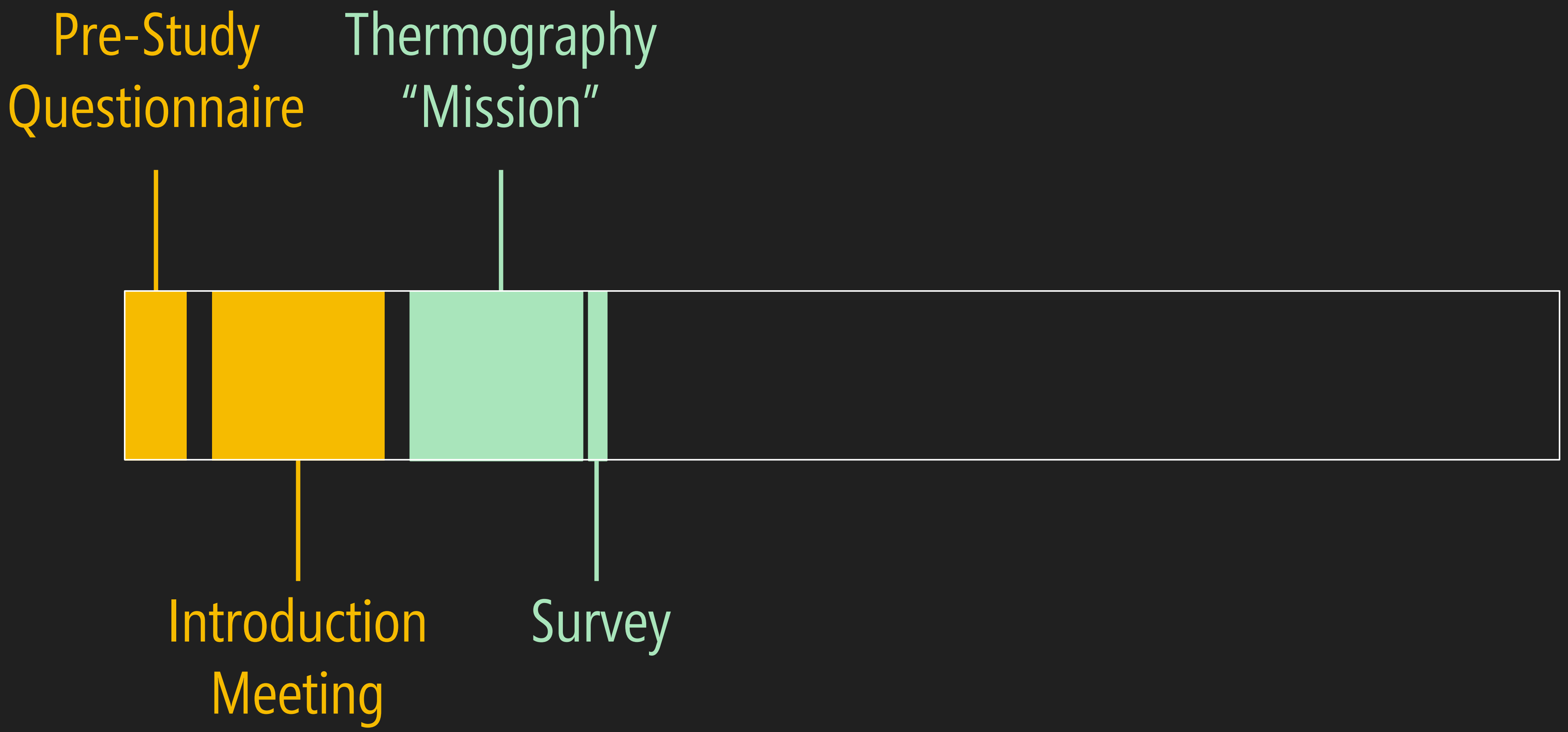


STUDY DESIGN: MISSIONS



"Investigate your home with your thermal camera for signs of energy inefficiencies; collect at least 25 photos that highlight aspects of your investigation."

Study Method: Field Study Procedure



Thermography Field Study: Weekly Questionnaire

Location

Please describe, to the best of your knowledge, the building(s) you explored during your mission.

6. What type of building(s) did you explore during your mission? *

- ○ House (i.e., a building completely separated from any others)
- ○ Apartment / Condo (i.e., a residence in a building with many others)
- ○ Townhouse / Row House (i.e., many homes sharing a wall with each other)
- ○ Warehouse
- ○ Office Building
- ○ Commercial Building
- ○ Manufacturing Building
- ○ Other - Write In (Required) ______ *

7. To the best of your knowledge, what materials were used in the construction of the building(s)? *

Photograph Descriptions

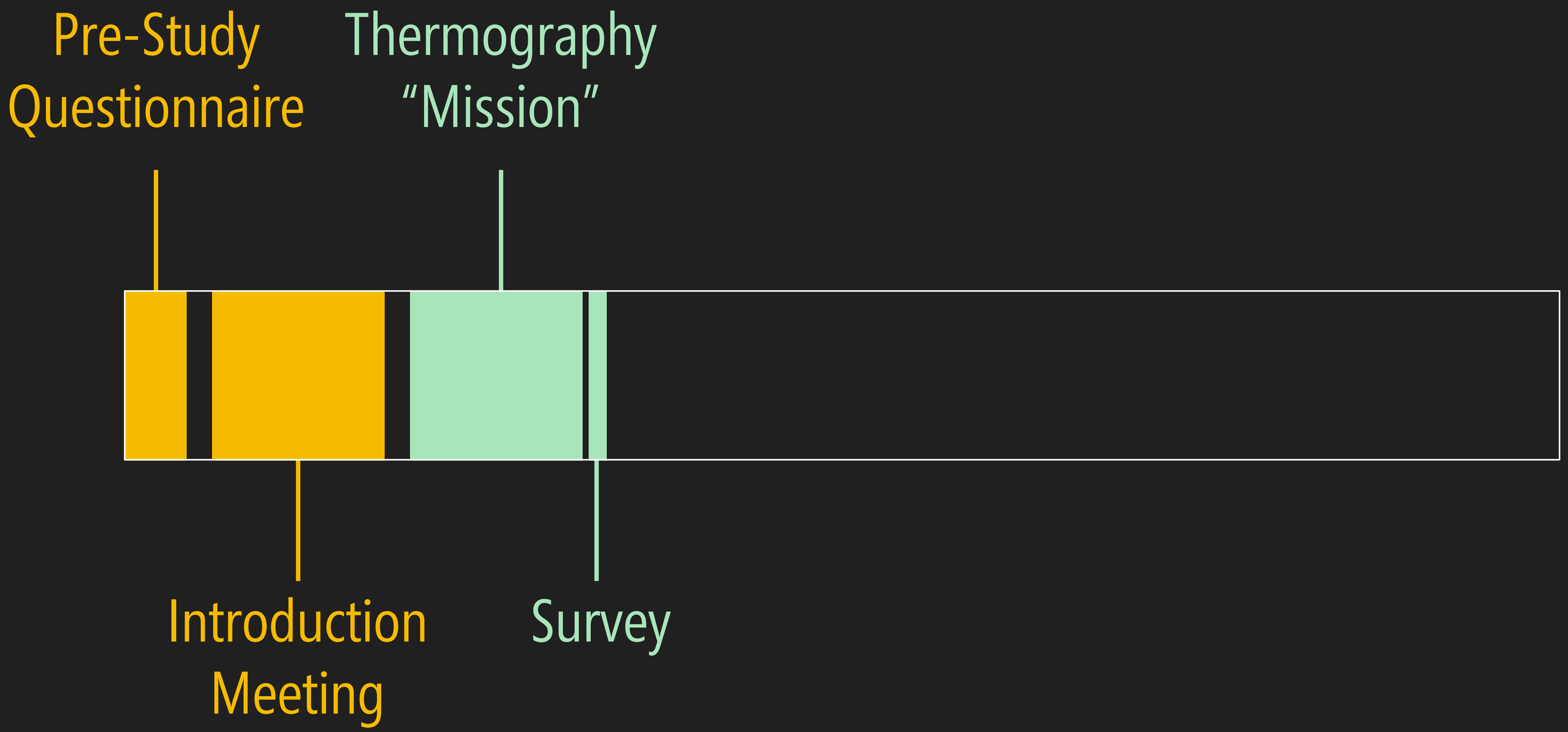
Please provide a brief summary of the images that you submitted

18. What types of issues did you look for during your mission? *

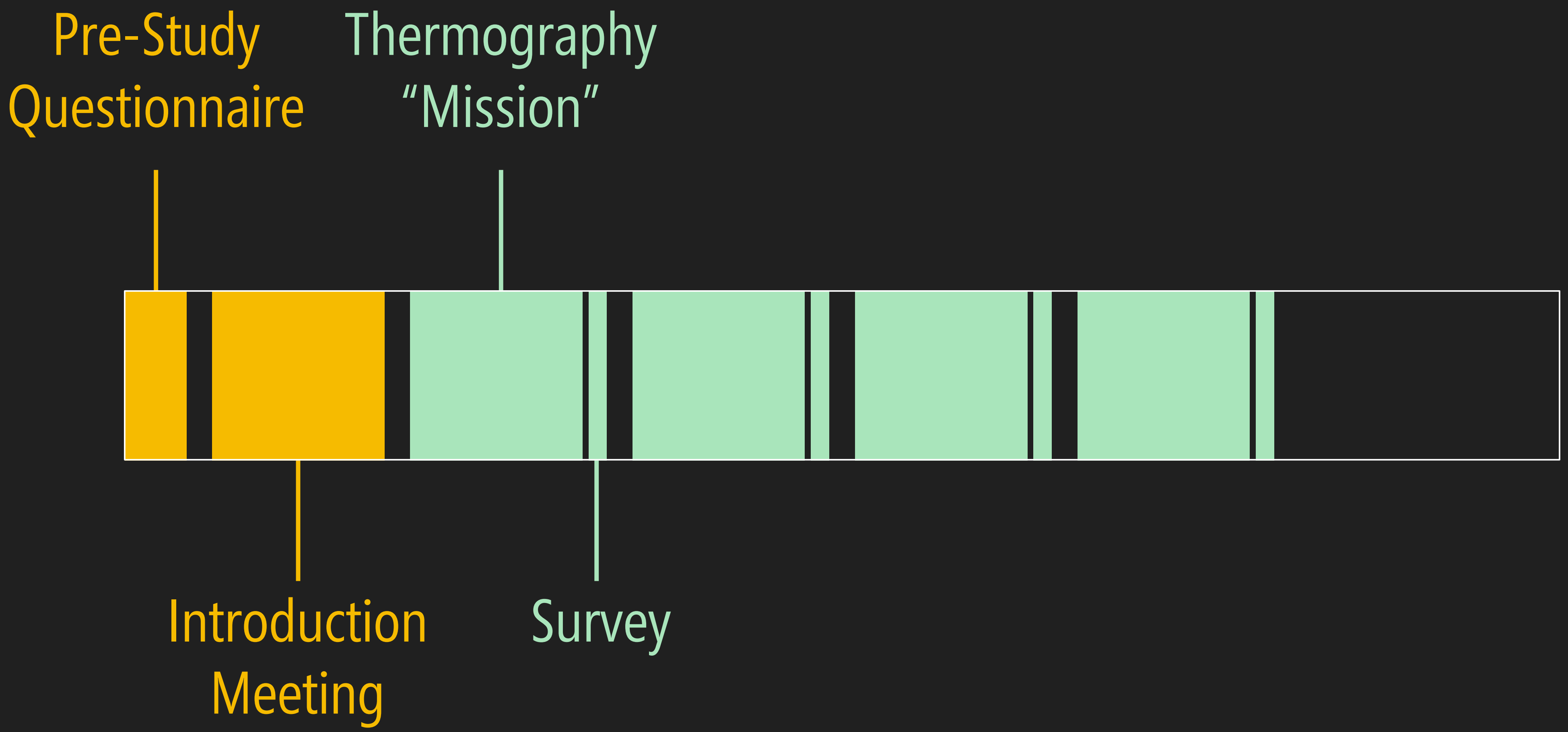
19. Did you find any evidence of issues (e.g., missing insulation)? *

20. Did you find anything else that interested you during your mission? *

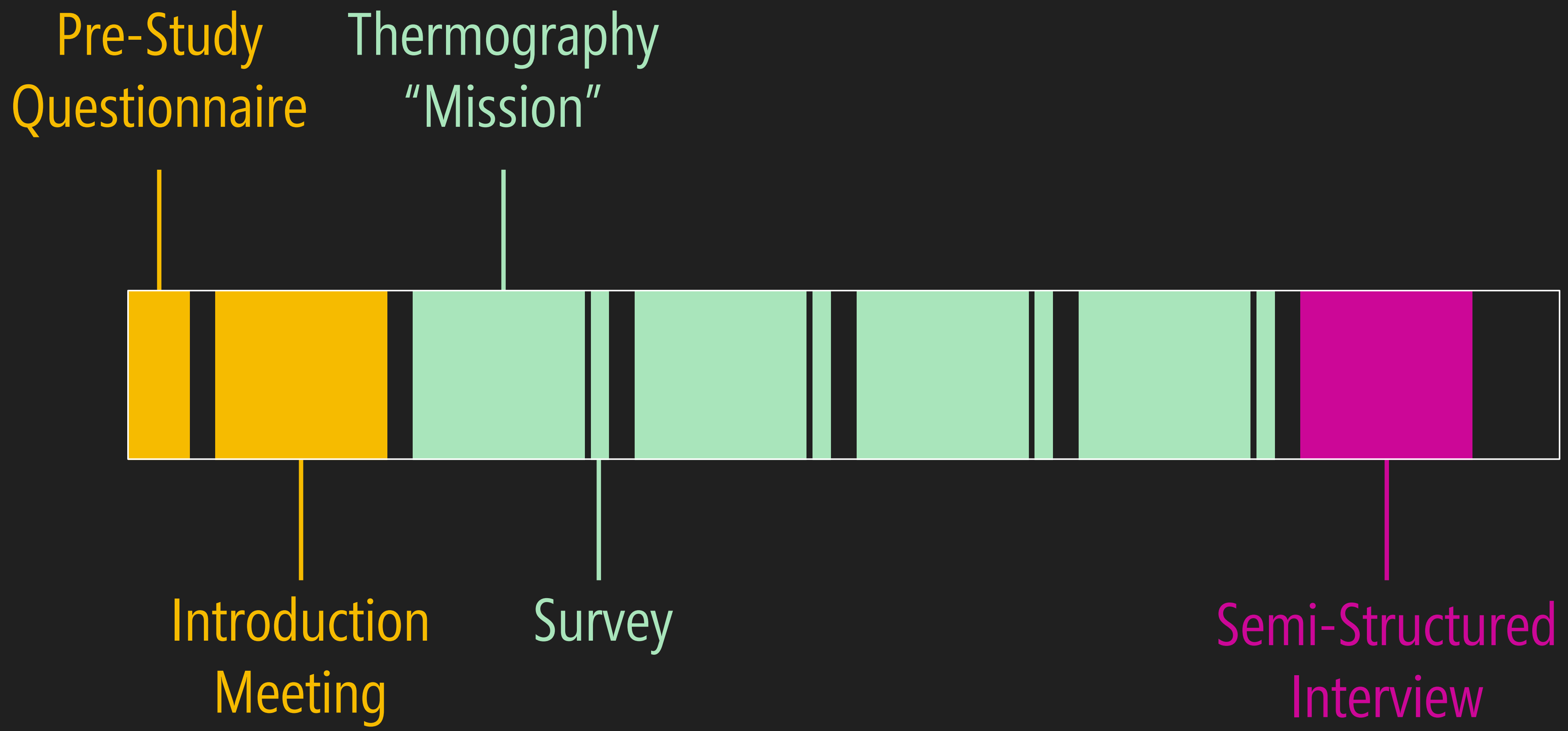
Study Method: Field Study Procedure



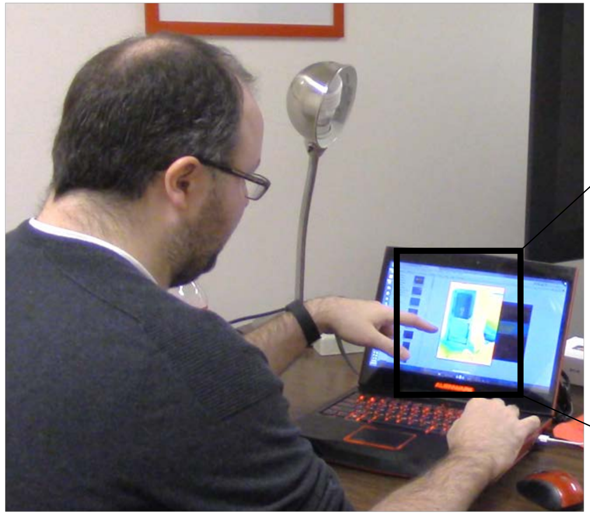
STUDY METHOD: FIELD STUDY PROCEDURE



Study Method: Field Study Procedure

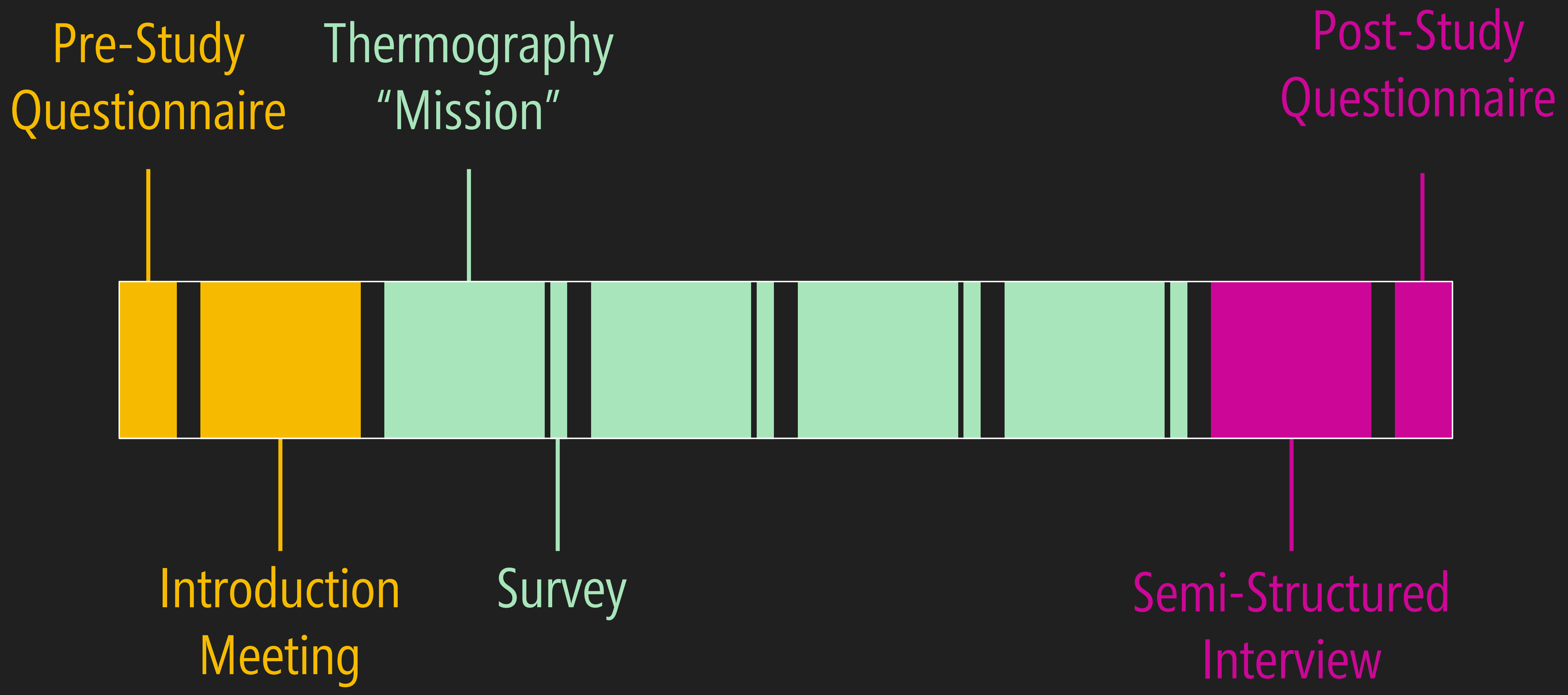


STUDY METHOD: SEMI-STRUCTURED INTERVIEW



"It was pretty clear to me that the air seals around this door were not doing a very good job of preventing cold air from leaking into this room." -P3

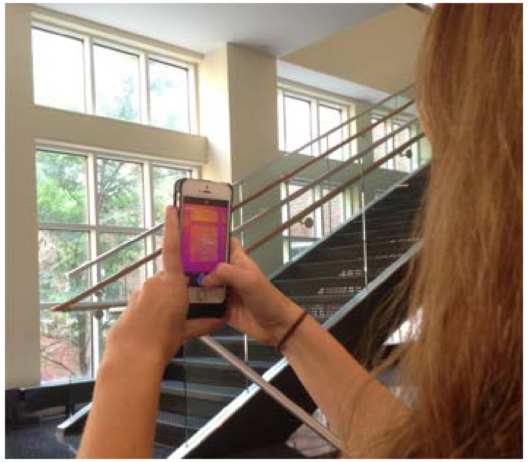
STUDY METHOD: FIELD STUDY PROCEDURE



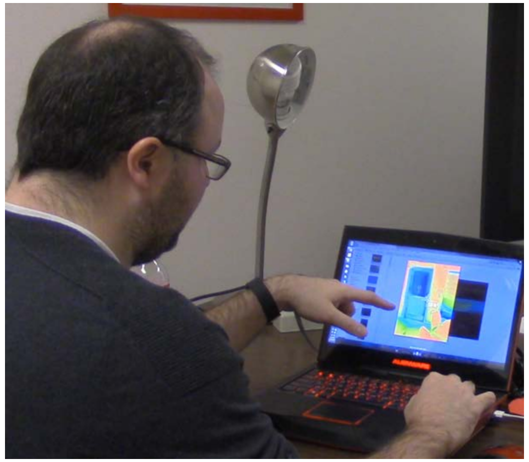
Study Method: Data Analysis

We qualitatively coded the survey, interview, and image data to uncover themes.

Study Findings

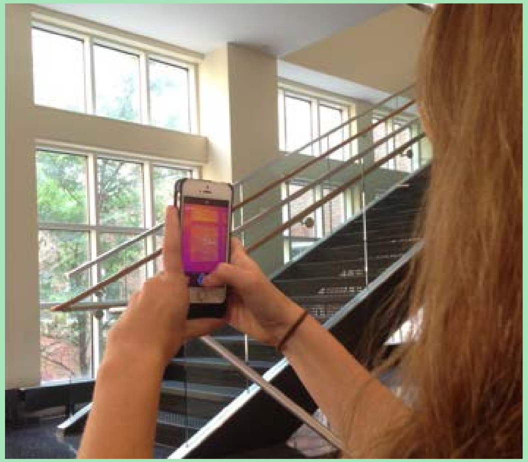


Field
Activities

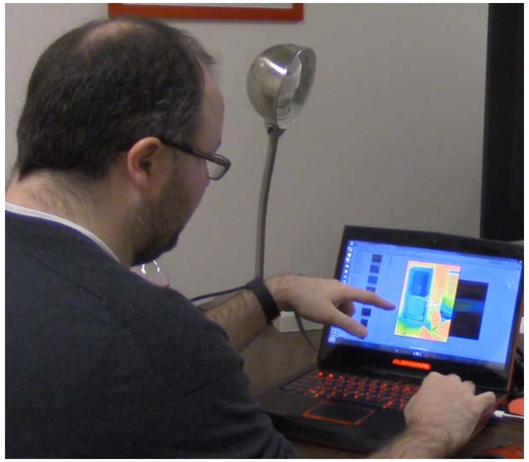


Semi-Structured
Interviews

Study Findings



Field
Activities



Semi-Structured
Interviews

Week

Home
Workplace
Commercial
Community

STUDY FINDINGS: FIELD ACTIVITIES

Week	Images
Home	572 (*Avg=52*)
Workplace	405 (*Avg=14*)
Commercial	415 (*Avg =16*)
Community	516 (*Avg =13*)
Total	*1,991* (*Avg=46*)

Study Findings: Field Activities

Week	**Images**	**Time (mins)**
Home	572 (*Avg=52*)	34 (*SD=15*)
Workplace	405 (*Avg=14*)	32 (*SD=14*)
Commercial	415 (*Avg =16*)	28 (*SD=16*)
Community	516 (*Avg =13*)	27 (*SD=16*)
Total	*1,991* (*Avg=46*)	*30*

STUDY FINDINGS: FIELD ACTIVITIES

STUDY FINDINGS: FIELD ACTIVITIES

Context

(a) Indoor (64.2%)

(b) Outdoor (35.6%)

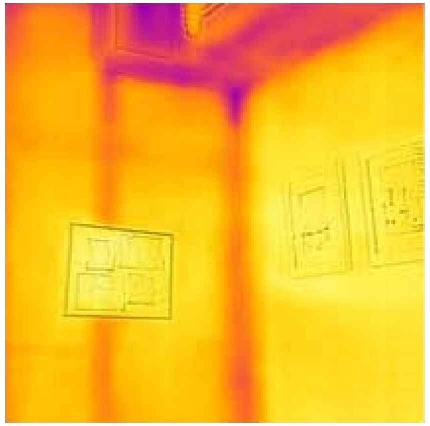
Study Findings: Field Activities

Context


(a) Indoor (64.2%)


(b) Outdoor (35.6%)

Subjects

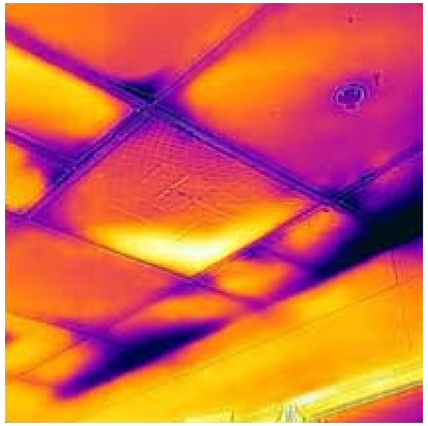

(c) Walls (71.6%)

(d) Windows (30.3%)

(e) Electronics (24.7%)

(f) Doors (24.4%)

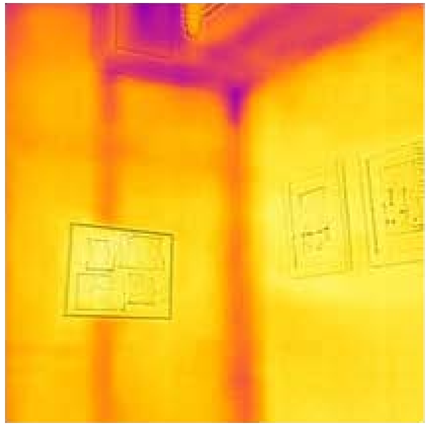

(g) Light Fixtures (23.8%)


(h) Ceilings (22.7%)

STUDY FINDINGS: FIELD ACTIVITIES

Context | **Subjects** | **Misc./Fun**

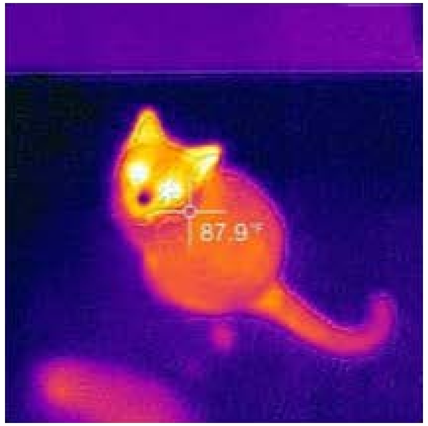
(a) Indoor (64.2%)



(c) Walls (71.6%)

(e) Electronics (24.7%)

(g) Light Fixtures (23.8%)

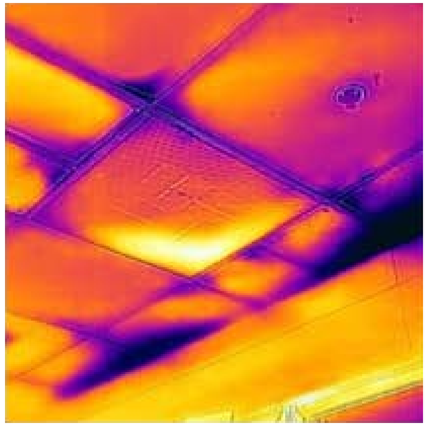


(i) People/Pets (4.7%)

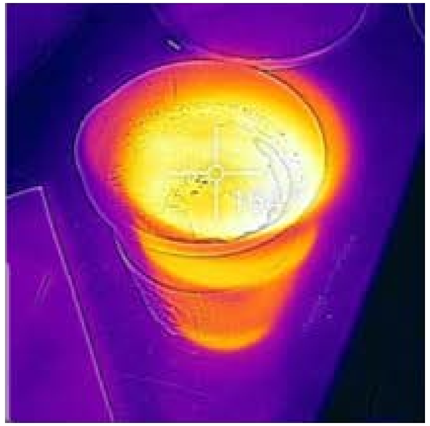
(b) Outdoor (35.6%)

(d) Windows (30.3%)

(f) Doors (24.4%)



(h) Ceilings (22.7%)



(j) Play/Experiments (1.0%)

STUDY FINDINGS: FIELD ACTIVITIES

Week	**Images**	**Time** (mins)
Home	**572** (*Avg=52*)	**34** (*SD=15)*
Workplace	**405** (*Avg=14*)	**32** (*SD=14*)
Commercial	415 (*Avg =16*)	28 (*SD=16*)
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Home Mission

During the home mission, participants:

- Collected 572 photos (AVG=57.2, SD=52.27).

Home Mission

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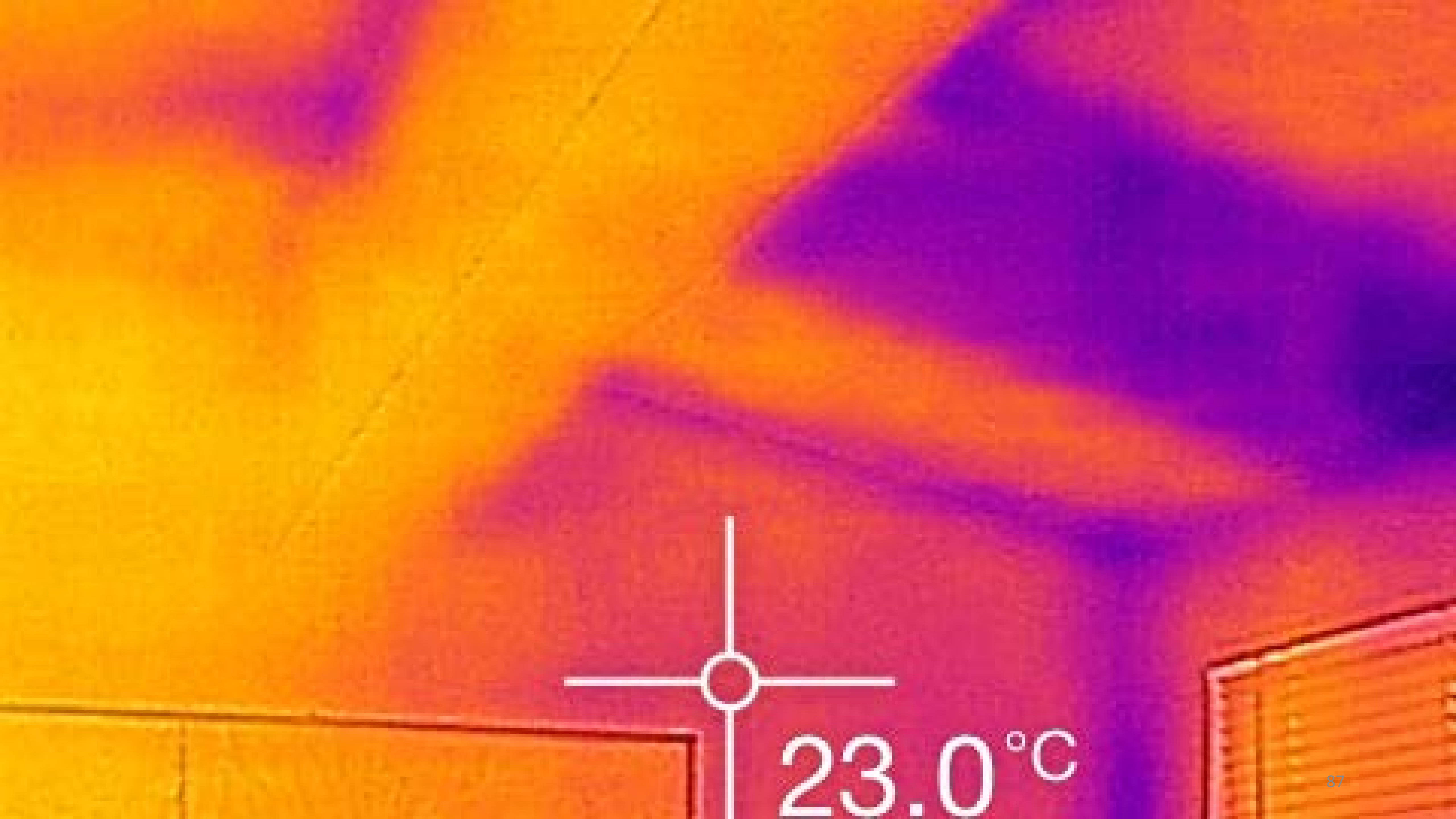
- Collected 572 photos (AVG=57.2, SD=52.27).
- Most (8) reported investigating pre-existing comfort issues.


66.8 °F


23.0°C

Home Mission

During the home mission, participants:

- Collected 572 photos (AVG=57.2, SD=52.27).
- Most (8) reported investigating pre-existing comfort issues.
- A few (3) reported investigating electrical issues due to safety concerns (*e.g.*, fire).

STUDY FINDINGS: FIELD ACTIVITIES

Week	Images	Time (mins)
Home	572 *(Avg=52)*	34 *(SD=15)*
Workplace	405 *(Avg=14)*	32 *(SD=14)*
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Workplace Mission

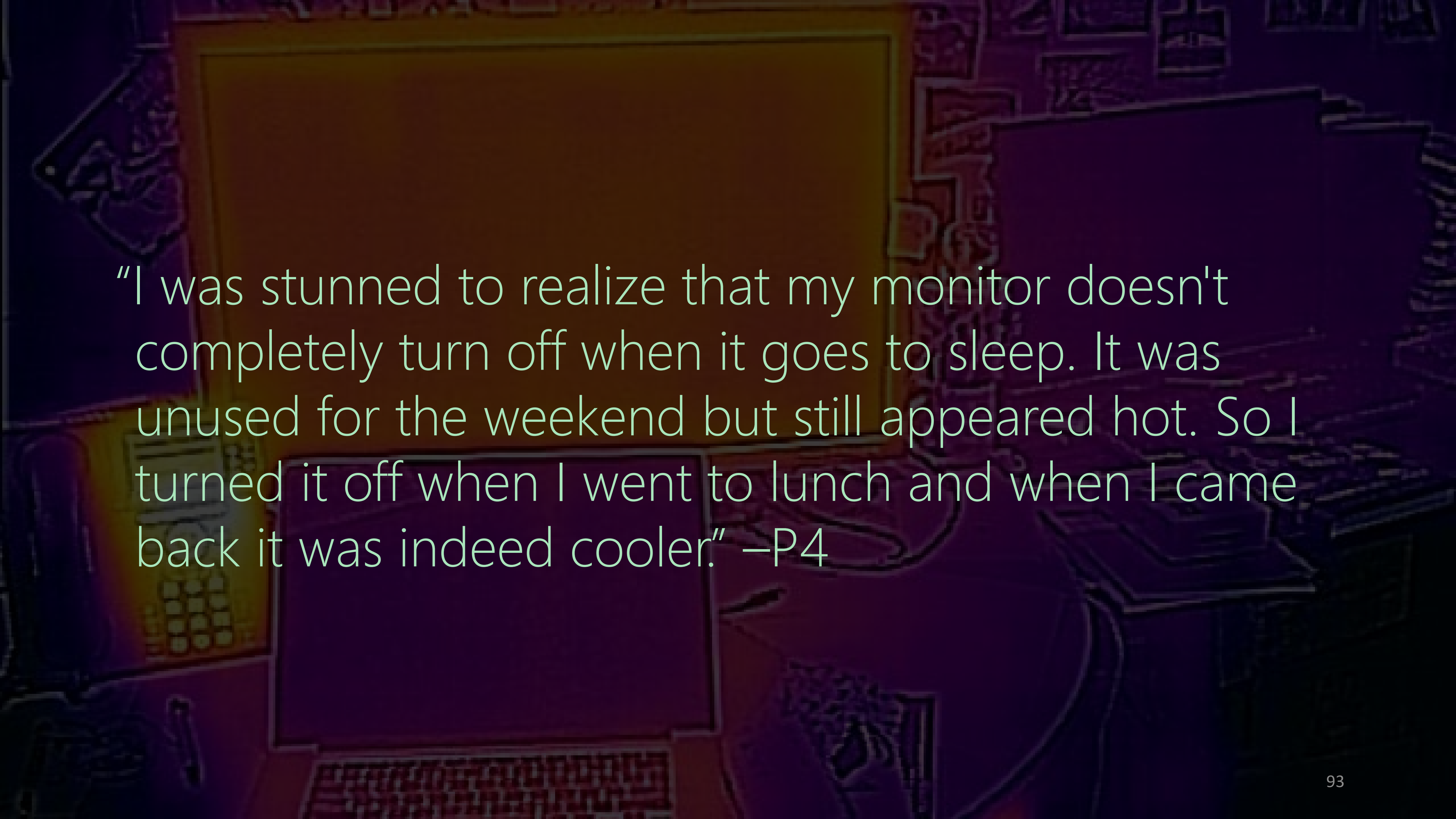
During the workplace missions, participants:

- Collected 405 photos (AVG=40.5, SD=18.02).

Workplace Mission

During the workplace missions, participants:

- Collected 405 photos (AVG=40.5, SD=18.02).
- All participants (10) reported looking for leaky windows, doors, and noted interesting heat signatures produced by electronic devices. Half (5) reported finding concerning issues.

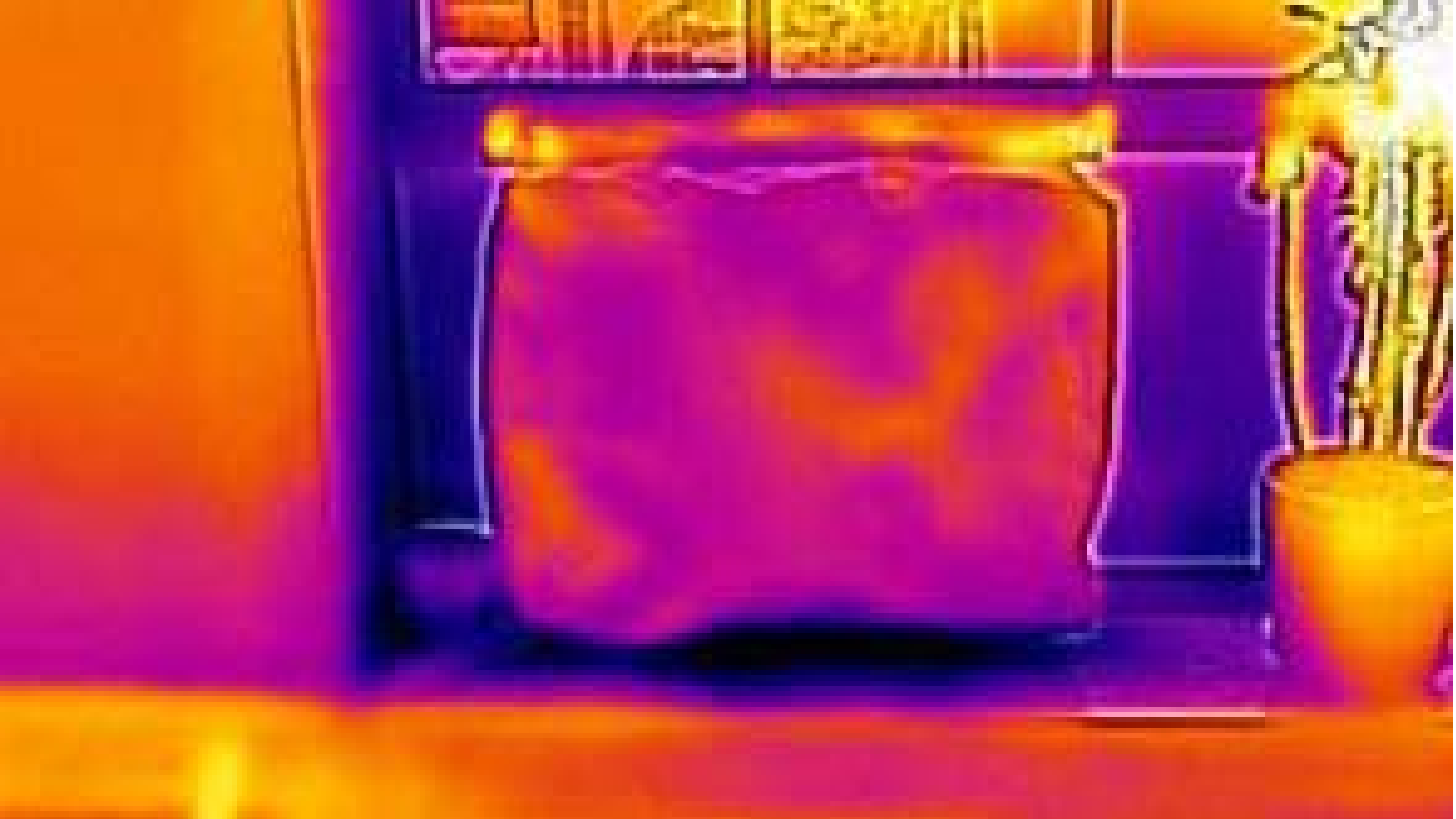


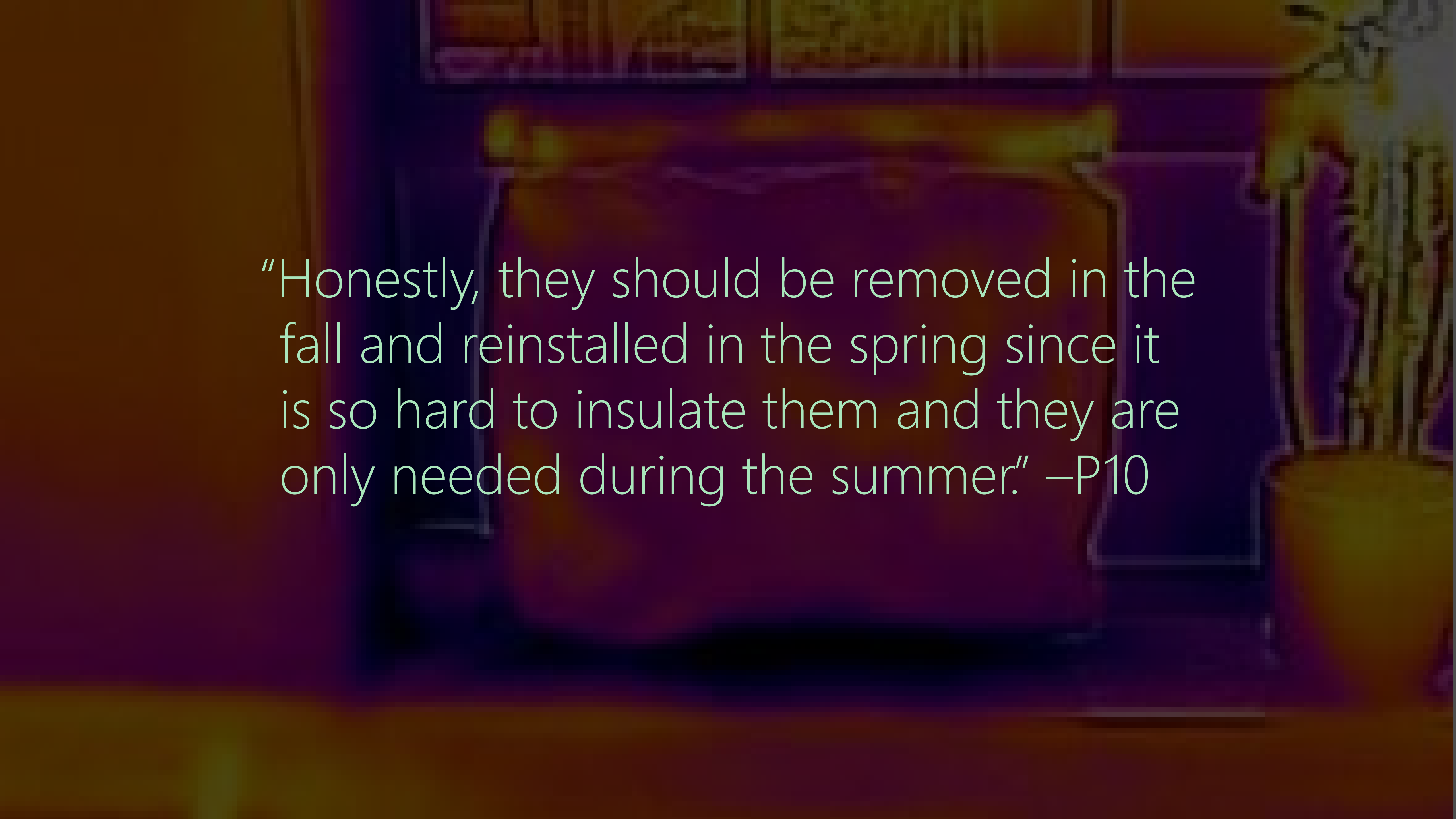
"I was stunned to realize that my monitor doesn't completely turn off when it goes to sleep. It was unused for the weekend but still appeared hot. So I turned it off when I went to lunch and when I came back it was indeed cooler." –P4

Workplace Mission

During the workplace missions, participants:

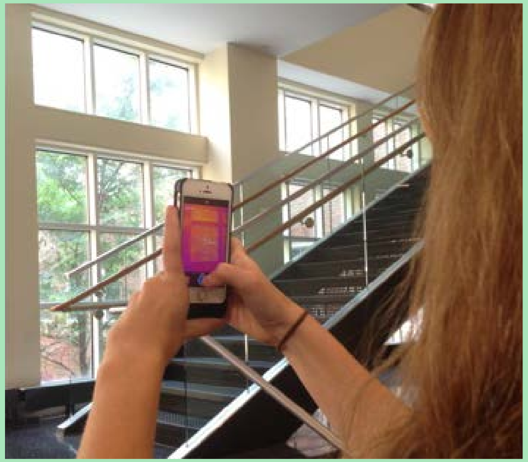
- Collected 405 photos (AVG=40.5, SD=18.02).
- All participants (10) reported looking for leaky windows, doors, and noted interesting heat signatures produced by electronic devices. Half (5) reported finding concerning issues.
- A few (2) explored comfort issues in shared office spaces.



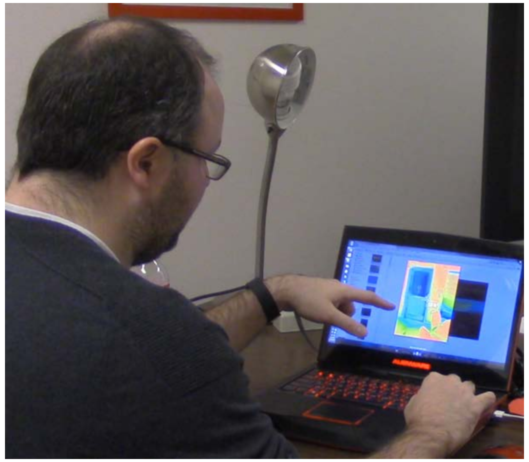


"Honestly, they should be removed in the fall and reinstalled in the spring since it is so hard to insulate them and they are only needed during the summer." –P10

STUDY FINDINGS

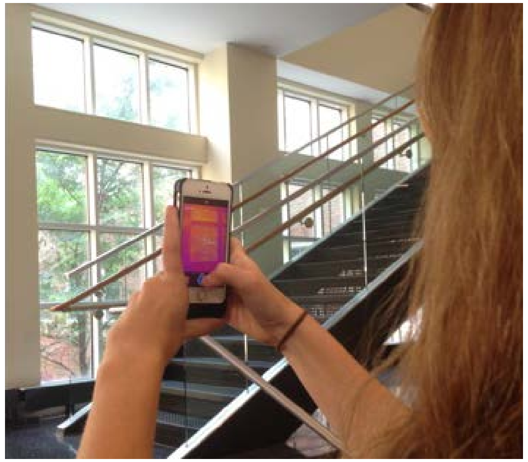


Field
Activities

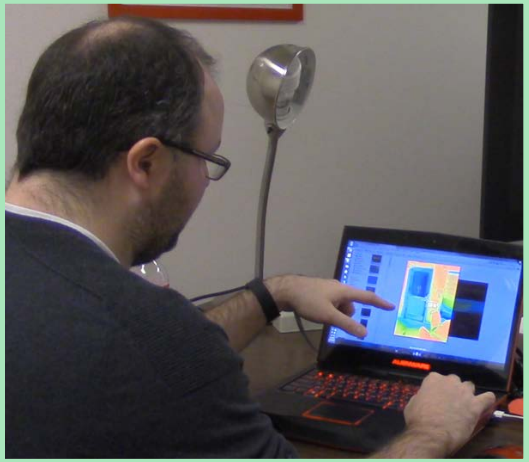


Semi-Structured
Interviews

Study Findings



Field
Activities



Semi-Structured
Interviews

STUDY FINDINGS: SEMI-STRUCTURE INTERVIEWS

Knowledge Discovery

Current Practices

Potential Benefits

Locus of Control

Hardware Issues

Software Issues

Interpretative Issues

Design Ideas

STUDY FINDINGS: SEMI-STRUCTURE INTERVIEWS

Knowledge Discovery

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STUDY FINDINGS: SEMI-STRUCTURE INTERVIEWS

Knowledge Discovery

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Potential Benefits

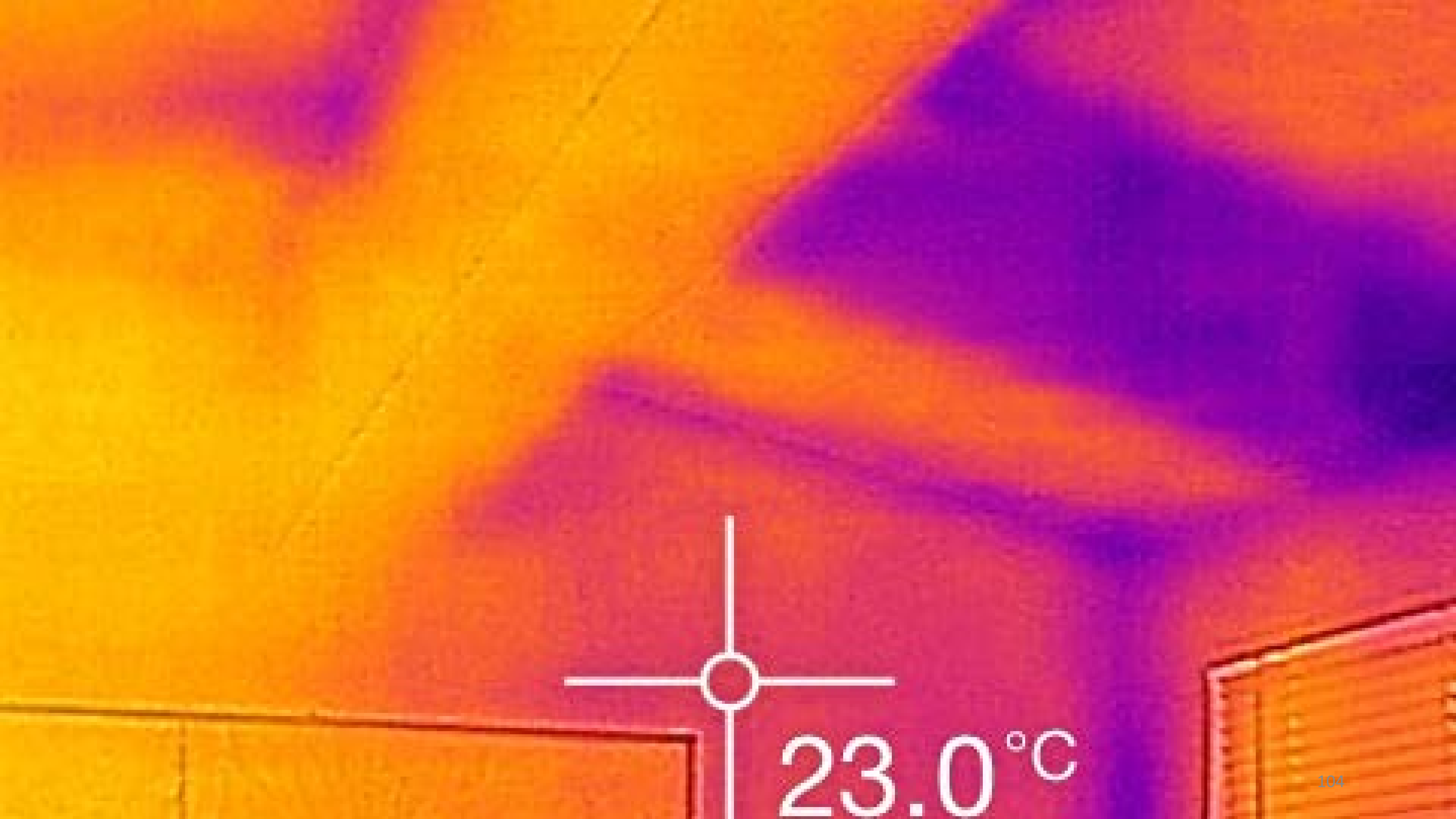
Participants thought that the benefits of their application of thermography included:

- All participants (10) considered the thermal camera a valuable investigative tool.

Potential Benefits

Participants thought that the benefits of their application of thermography included:

- All participants (10) considered the thermal camera a valuable investigative tool.
- Most (8) suggested that thermal imagery could provide supporting evidence for decisions makers with respect to making retrofit decisions.


23.0°C

"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." -P7

Study Findings: Semi-Structured Interviews

Knowledge Discovery	Hardware Issues
Current Practices	Software Issues
Potential Benefits	**Interpretative Issues**
Locus of Control	Design Ideas

Interpretative Issues

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- All participants (10) described capturing imagery that they could comfortably interpret and imagery that they did not understand.

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Interpretative Issues

Participants frequently discussed challenges associated with their ability to interpret issues they discovered:

- All participants (10) described capturing imagery that they could comfortably interpret and imagery that they did not understand.
- Most (8) believed that their ability to interpret thermographic images was limited by confounding variables (*e.g.*, heating elements, lack of materials knowledge).
- More than half (6) found it difficult to determine the significance of an issue they discovered.

"I don't know how much this really affects the energy use of my apartment." -P2

Study Findings: Semi-Structured Interviews

Knowledge Discovery

Current Practices

Potential Benefits

Locus of Control

Hardware Issues

Software Issues

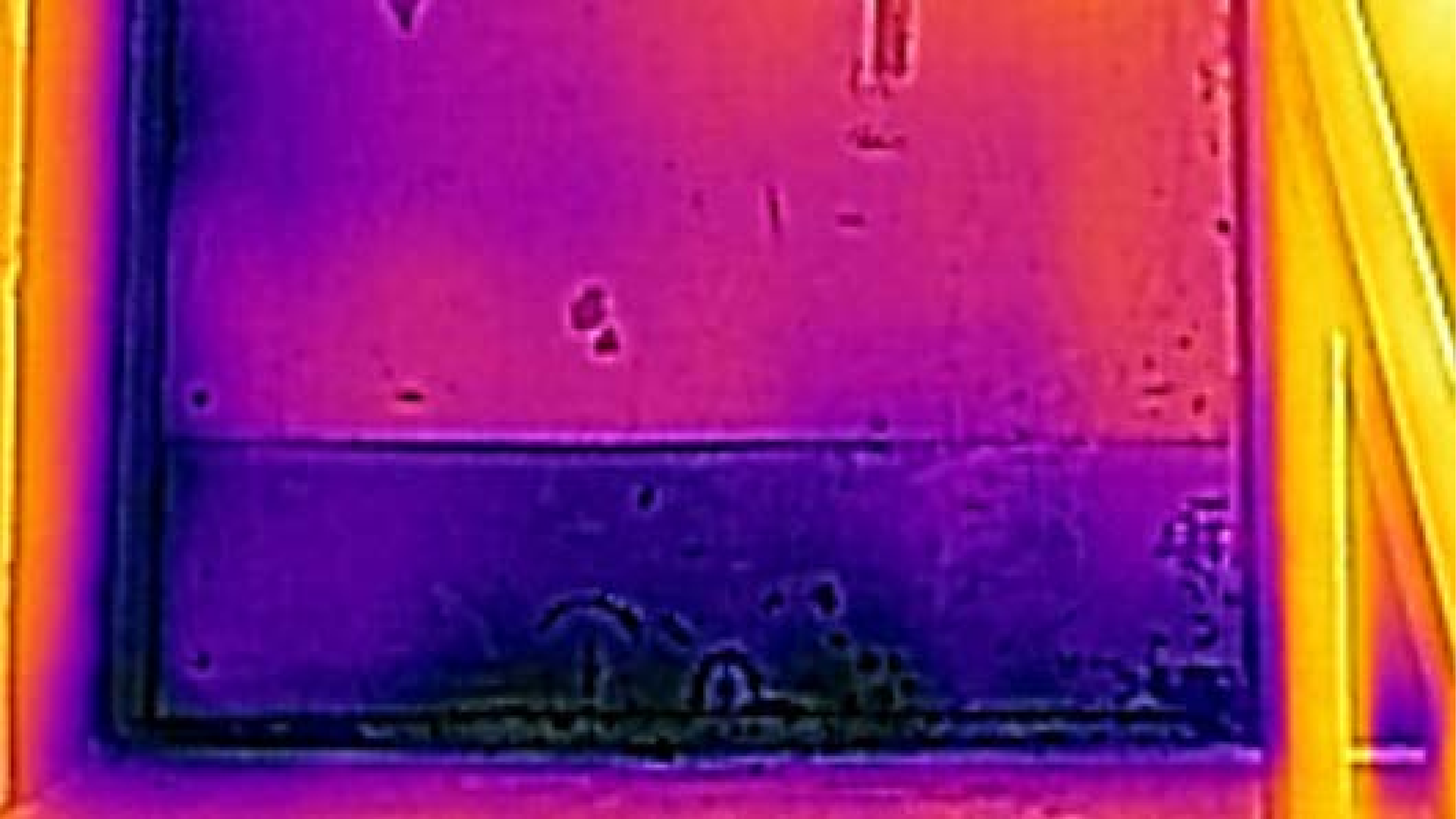
Interpretative Issues

Design Ideas

Locus of Control

Participants frequently discussed challenges associated with their ability to effect change:

- 4 participants (who rented or lived in a housing cooperative) were concerned that if they found evidence of a problem they would not be in a position to make retrofit decisions.



"If I took a picture that showed an issue, I don't necessarily think the owner would get on top of fixing it." -P5

Novice Smartphone Field Study: Research Outcomes

- **Further characterize novice use** of thermal cameras for building energy auditing activities

- **Highlights perceived benefits**—such as having being able to investigate and collect supporting evidence about efficiency issues

- **Outlines 4 primary barriers to novice building thermography** including lack of knowledge of building practices and material properties.

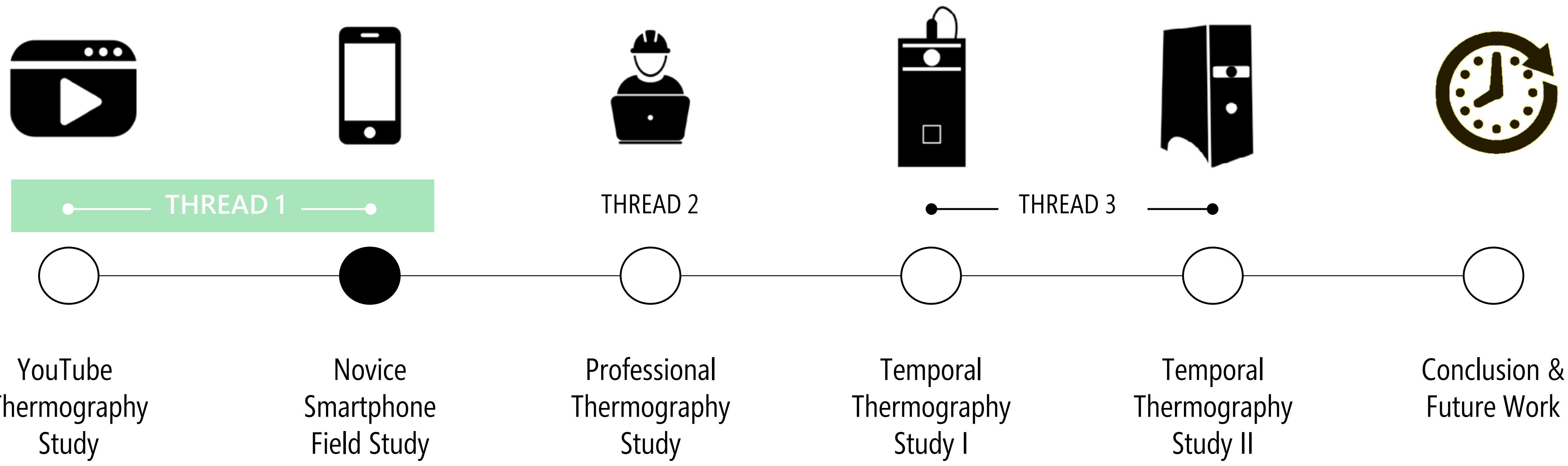
Thread 1 Takeaways: Novice Studies

Novice thermography influences renovation and retrofits decisions leading to (self-described) impact on residential energy savings.

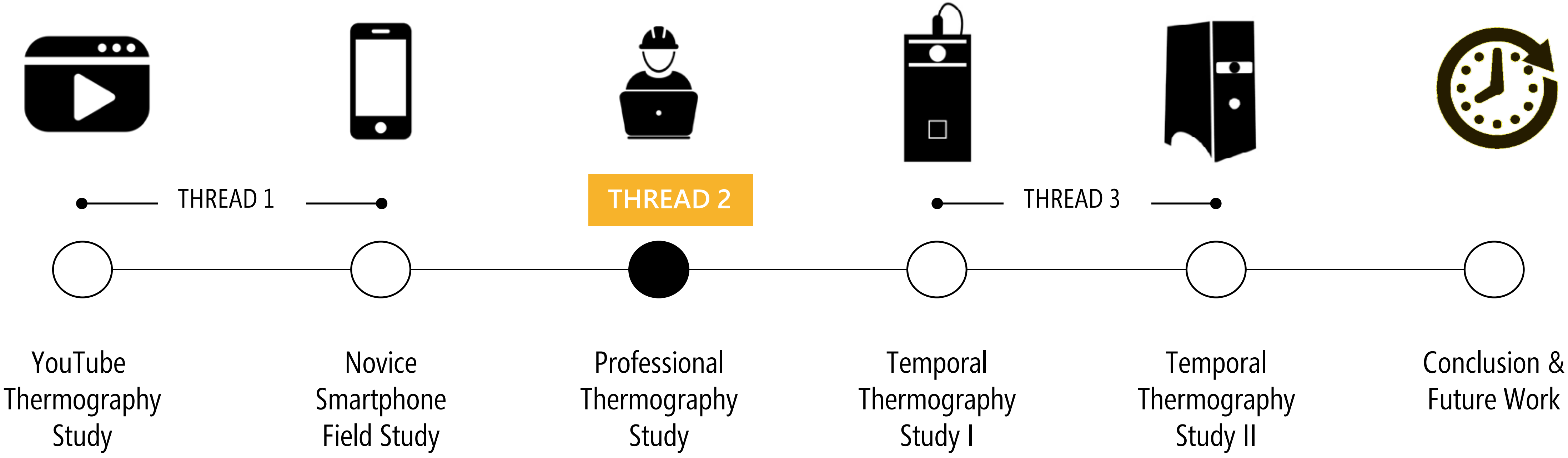
However, novice users may have difficulty determining:

- Whether or not problems exist
- Severity of problems found
- What actions to take

DISSERTATION OVERVIEW

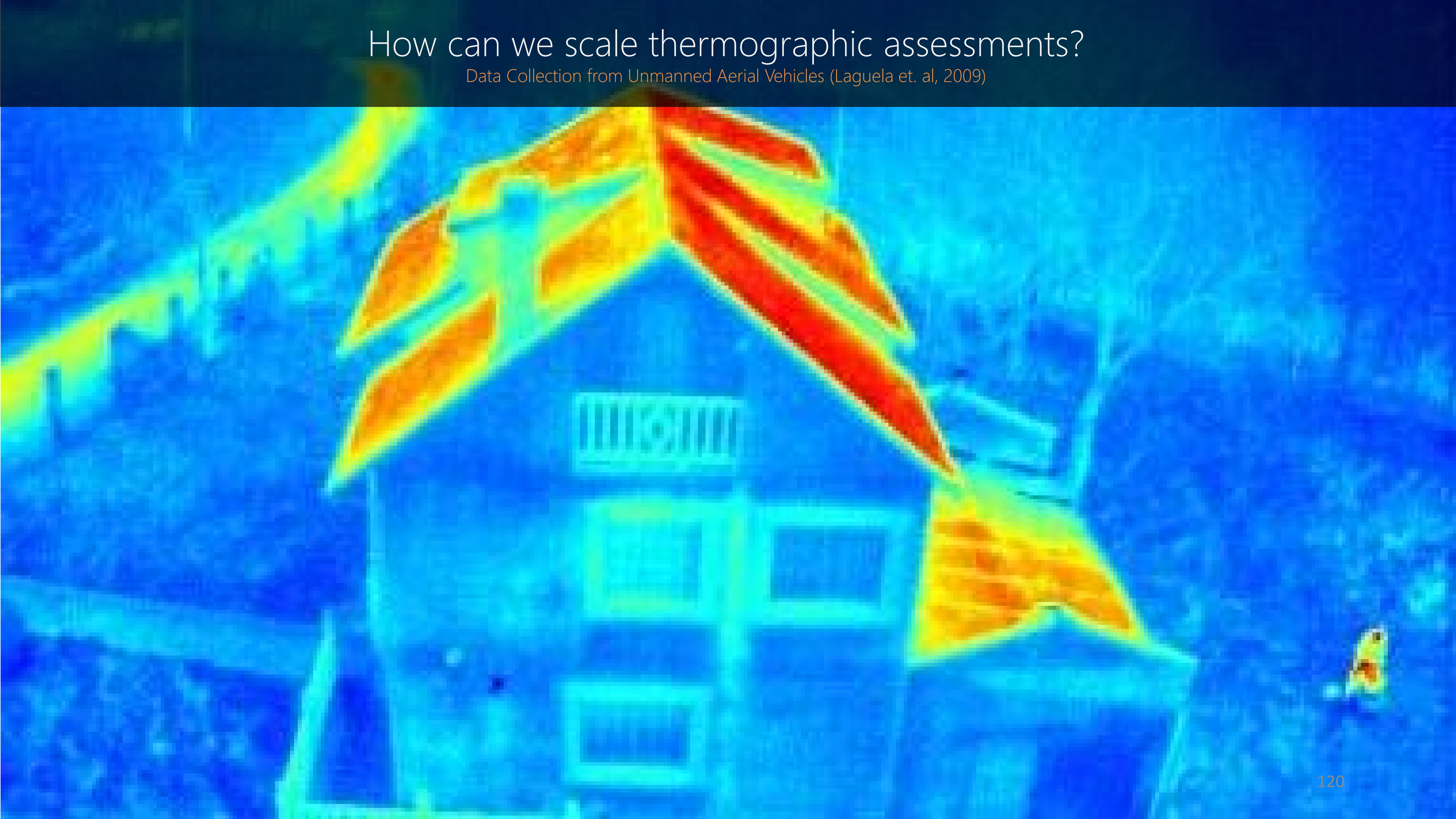


DISSERTATION OVERVIEW



How can we scale thermographic assessments?

Data Collection from Unmanned Aerial Vehicles (Laguela et. al, 2009)



How can we scale thermographic assessments?

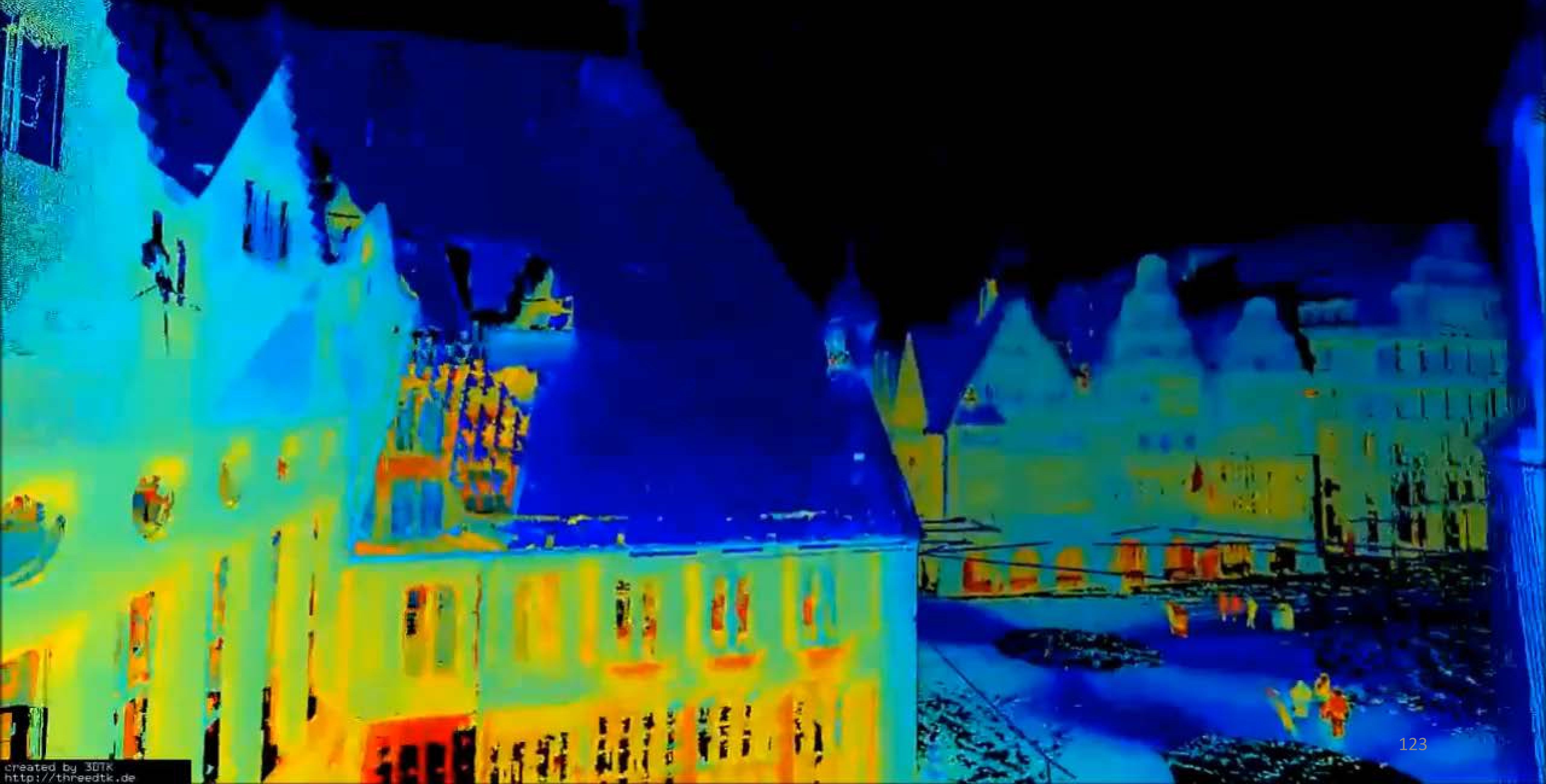
Energy Auditing Backpack (Oreifej *et al.* 2014)

How can we scale thermographic assessments?

Car Mounted Thermographic Cameras (Essess Inc., 2013)

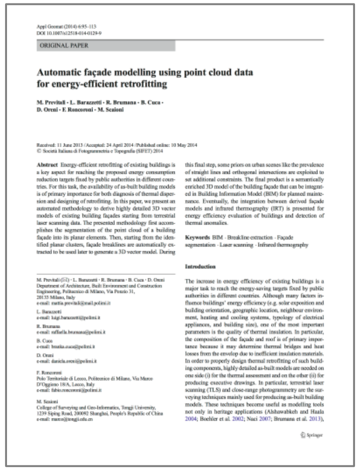
How can we scale thermographic assessments?

High Fidelity Model Generation



No Human Perspective in Automated Thermography Literature

Reviewed over 30 papers in 'automated thermography.' No user studies, no investigations of how human auditors may use or perceive emerging systems, no discussions of human-centered design, etc.


Automatic façade modelling using point cloud data for energy-efficient retrofitting

Previtali *et al.,Applied Geomatics'14*


A mobile robot based system for fully automated thermal 3D mapping

Bormann *et al., Adv. Eng. Informatics'14*


Aerial oblique thermographic imagery for the generation of building 3D models to complement Geographic Information Systems

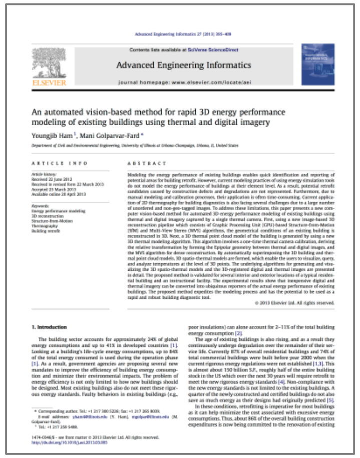
Laguela *et al., Q. Infrared Thermography'14*


Energy efficiency studies through 3D laser scanning and thermographic technologies

Laguela *et al., Energy and Buidlings'14*


THERMOGRAPHIC ANALYSIS FROM UAV PLATFORMS FOR ENERGY EFFICIENCY RETROFIT APPLICATIONS

Previtali *et al., J. Mobile Multimedia'14*


An automated vision-based method for rapid 3D energy performance modeling of existing buildings using thermal and digital imagery

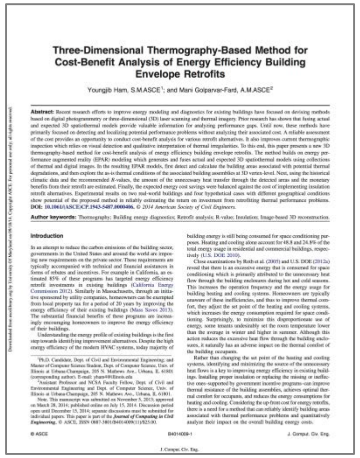
Ham*et al., Adv. Eng. Informatics'13*


Real-time Mobile 3D Temperature Mapping

Vidas *et al., IEEE Sensors'14*


As-Is 3D Thermal Modeling for Existing Building Envelopes Using a Hybrid LIDAR System

Wang *et al., J. Comp. Civil Engineering'13*


Three-Dimensional Thermography-Based Method for Cost-Benefit Analysis of Energy Efficiency Building Envelope Retrofits

Ham *et al., J. Comp. Civil Engineering'14*

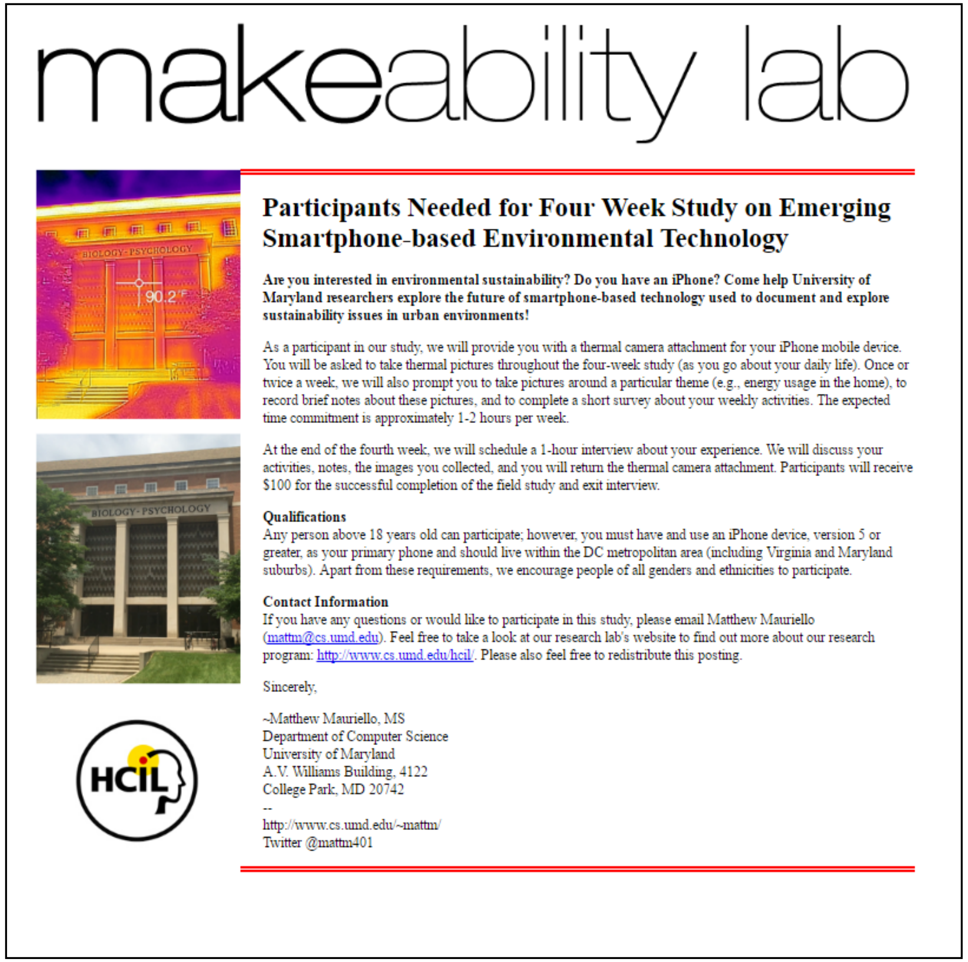

Interpreting Thermal 3D Models of Indoor Environments for Energy Efficiency

Demisse *et al., Intl. Conf. Adv. Robotics'13*

PROFESSIONAL THERMOGRAPHY STUDY: RESEARCH QUESTIONS

1. How is thermography currently being used by professional energy auditors?
2. What benefits and drawback do these auditors identify when envisioning the use of robotics for thermographic data collection?
3. What are the implications for the design of these automated thermography tools?

STUDY DESIGN: RECRUITMENT



makeability lab

Participants Needed for Four Week Study on Emerging Smartphone-based Environmental Technology

Are you interested in environmental sustainability? Do you have an iPhone? Come help University of Maryland researchers explore the future of smartphone-based technology used to document and explore sustainability issues in urban environments!

As a participant in our study, we will provide you with a thermal camera attachment for your iPhone mobile device. You will be asked to take thermal pictures throughout the four-week study (as you go about your daily life). Once or twice a week, we will also prompt you to take pictures around a particular theme (e.g., energy usage in the home), to record brief notes about these pictures, and to complete a short survey about your weekly activities. The expected time commitment is approximately 1-2 hours per week.

At the end of the fourth week, we will schedule a 1-hour interview about your experience. We will discuss your activities, notes, the images you collected, and you will return the thermal camera attachment. Participants will receive $100 for the successful completion of the field study and exit interview.

Qualifications
Any person above 18 years old can participate; however, you must have and use an iPhone device, version 5 or greater, as your primary phone and should live within the DC metropolitan area (including Virginia and Maryland suburbs). Apart from these requirements, we encourage people of all genders and ethnicities to participate.

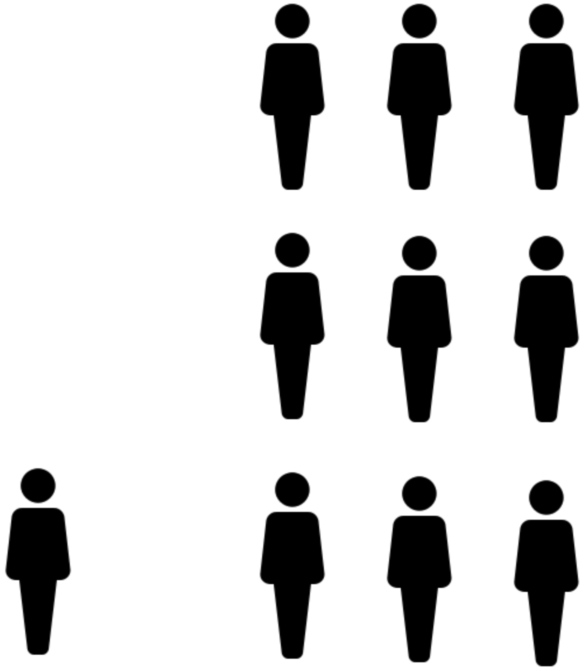
Contact Information
If you have any questions or would like to participate in this study, please email Matthew Mauriello (mattm@cs.umd.edu). Feel free to take a look at our research lab's website to find out more about our research program: http://www.cs.umd.edu/hcil/. Please also feel free to redistribute this posting.

Sincerely,

~Matthew Mauriello, MS
Department of Computer Science
University of Maryland
A.V. Williams Building, 4122
College Park, MD 20742
--
http://www.cs.umd.edu/~mattm/
Twitter @mattm401

We recruited participants using listserv and community message boards.

STUDY METHOD: PARTICIPANTS



10 Participants (1 Female)

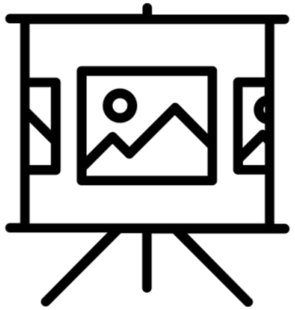
Average Age: 44.8 Years

Average Exp.: 6.7 Years

STUDY METHOD: THREE-PARTS

Study 1

Part 1:
Semi-Structured Interviews
~50 Minutes



Part 2:
Presentation of Design Probes
~40 Minutes

Study 2

Observational Case Study:
Residential Energy Audit
~120 Minutes

STUDY METHOD: SEMI-STRUCTURED INTERVIEWS

- Background
- Practices and Procedures
- Challenges
- Thermography Data
- Strengths and Weakness
- Sustainability and Energy Efficiency
- The Future of Thermography

STUDY METHOD: PRESENTATION OF DESIGN PROBES

Scenario 1
(Text)

Scenario 2
(Text)

Scenario 3
(Text)

STUDY METHOD: PRESENTATION OF DESIGN PROBES

Scenario 1
(Text)

Scenario 2
(Text)

Scenario 3
(Text)

Scenario 4
(Video)

Study Method: Presentation of Design Probes

Scenario 1
(Text)

Scenario 2
(Text)

Scenario 3
(Text)

Scenario 4
(Video)

Scenario 5
(Mid-Fi Prototype)

Study Method: Presentation of Design Probes

Scenario 1 (Text)

Scenario 2 (Text)

Scenario 3 (Text)

Scenario 4 (Video)

Scenario 5 (Mid-Fi Prototype)

"You are responsible for a small fleet of **thermography UAVs**. The UAVs fly around **semi-autonomously** collecting thermal data about each building on your campus. When abnormalities are detected, the UAVs are programmed to more closely examine these areas and provide **high resolution reports** of potential problems. The UAVs reduce labor costs compared with manual assessments, can investigate otherwise **inaccessible areas** of buildings (e.g., high exterior floors), and enable **historical reports** showing thermal **performance over time**."

Study Method: Presentation of Design Probes

Scenario 1
(Text)

Scenario 2
(Text)

Scenario 3
(Text)

Scenario 4
(Video)

Scenario 5
(Mid-Fi Prototype)

Scenario 5 (Mid-Fi Prototype)

3D Reconstruction, Anomaly Detection, Temporal Analysis

After the data is collected, it is time to begin your analysis.

Study Method: Data Analysis

We qualitatively coded the interview and design probe data to uncover themes.

STUDY FINDINGS: SEMI-STRUCTURED INTERVIEWS

Required Knowledge

Client Interactions

Challenges

Study Findings: Semi-Structured Interviews

Required Knowledge

Client Interactions

Challenges

REQUIRED KNOWLEDGE

Participants frequently discussed knowledge required to perform thermographic audits:

- 6 of 10 auditors felt that an understanding of building materials and construction were necessary for proper thermographic inspections.

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Participants frequently discussed knowledge required to perform thermographic audits:

- 6 of 10 auditors felt that an understanding of building materials and construction were necessary for proper thermographic inspections.

- 5 of 10 auditors expressed that a understanding of the physics behind heat transfer and airflow were crucial to interpreting results.

"The thing that is most critical to understand is how heat behaves and interacts with different materials." –P1

Study Findings: Semi-Structured Interviews

Required Knowledge

Client Interactions

Challenges

Study Findings: Semi-Structured Interviews

Required Knowledge

Client Interactions

Challenges

CHALLENGES

All of our energy auditors brought up challenges related to the practice of thermography, especially related to:

- Weather

CHALLENGES

All of our energy auditors brought up challenges related to the practice of thermography, especially related to:

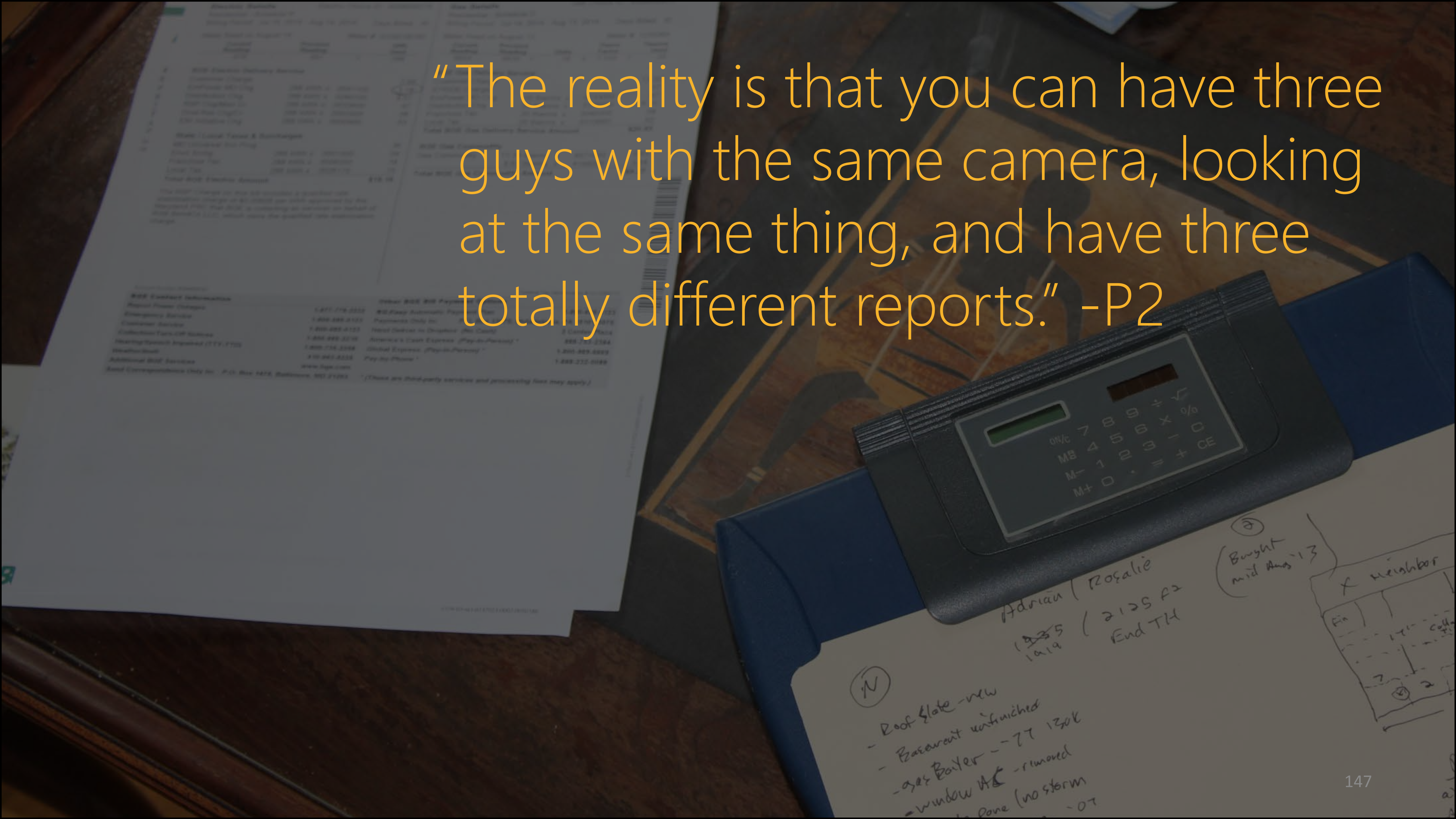
- Weather
- Untrained or undereducated practitioners

STUDY FINDINGS: SEMI-STRUCTURED INTERVIEWS

CHALLENGES

All of our energy auditors brought up challenges related to the practice of thermography, especially related to:

- Weather
- Untrained or undereducated practitioners
- Difficulty of interpreting results



"The reality is that you can have three guys with the same camera, looking at the same thing, and have three totally different reports." -P2

STUDY FINDINGS: DESIGN PROBES

Automation Benefits

Concerns

Automation Benefits

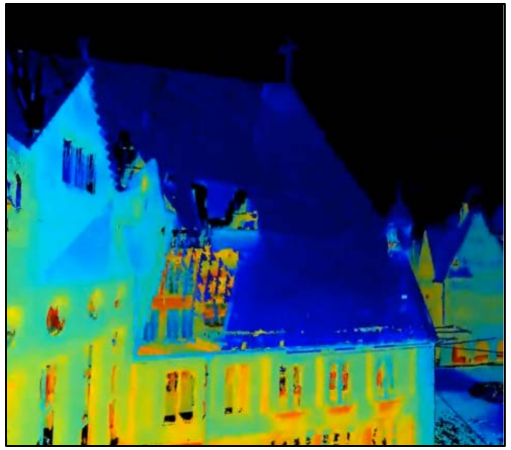
Concerns

STUDY FINDINGS: DESIGN PROBES, AUTOMATION BENEFITS

Saving time and money

STUDY FINDINGS: DESIGN PROBES, AUTOMATION BENEFITS

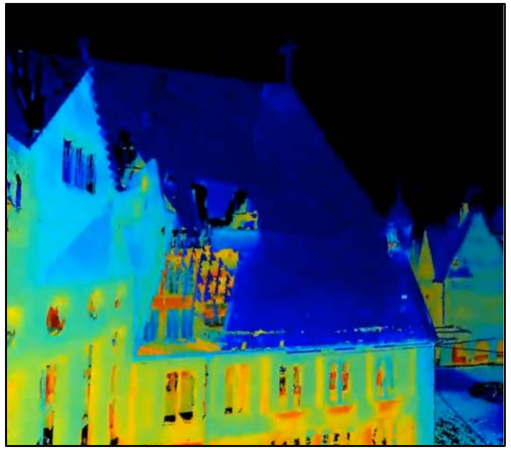
Saving time and money



Assessing inaccessible areas

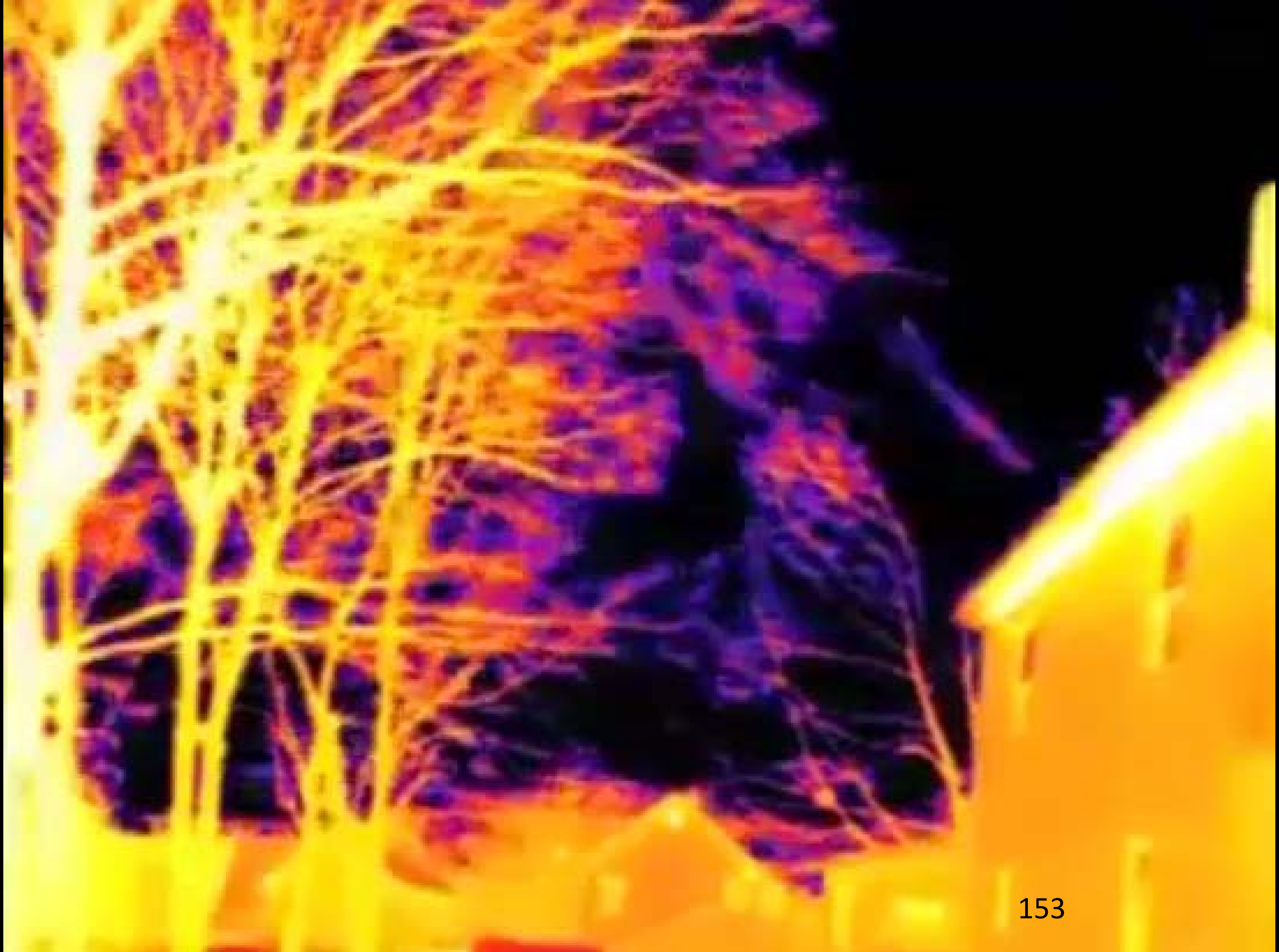
Study Findings: Design Probes, Automation Benefits

Saving time and money



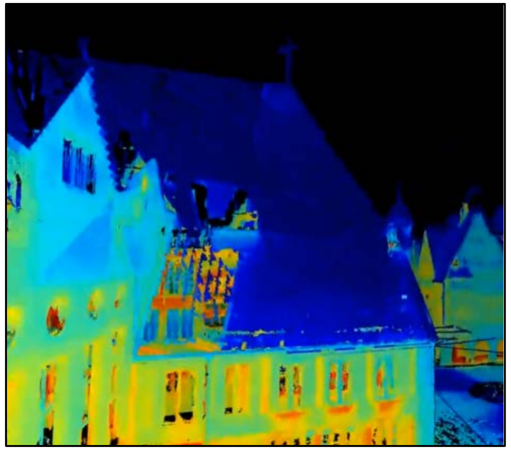
Assessing inaccessible areas

Scaling up data collection



STUDY FINDINGS: DESIGN PROBES, AUTOMATION BENEFITS

Saving time and money

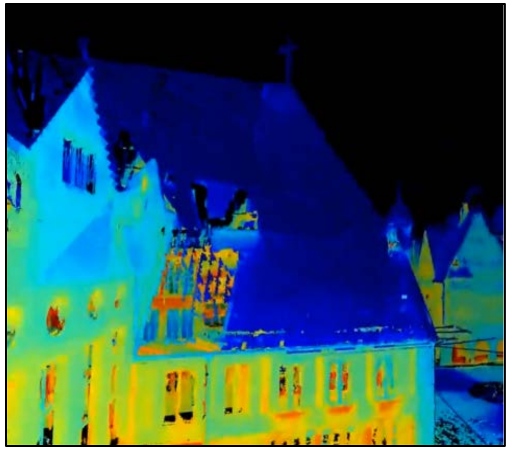


Assessing inaccessible areas

Scaling up data collection

Study Findings: Design Probes, Automation Benefits

Saving time and money



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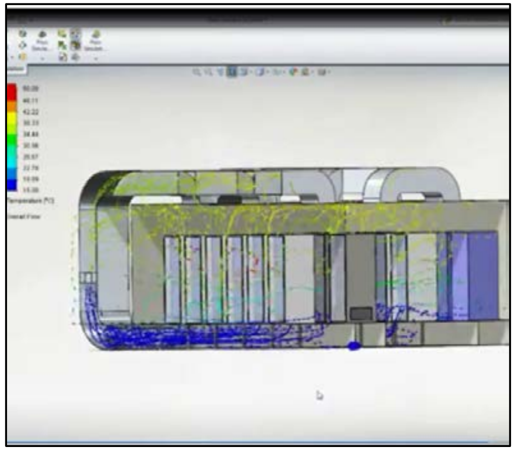
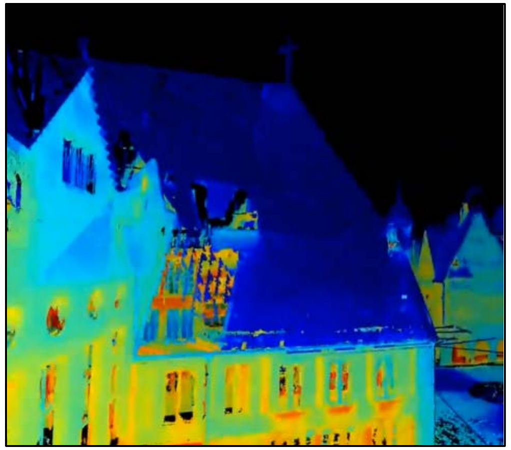


New types of analyses

Study Findings: Design Probes, Automation Benefits

Saving time and money



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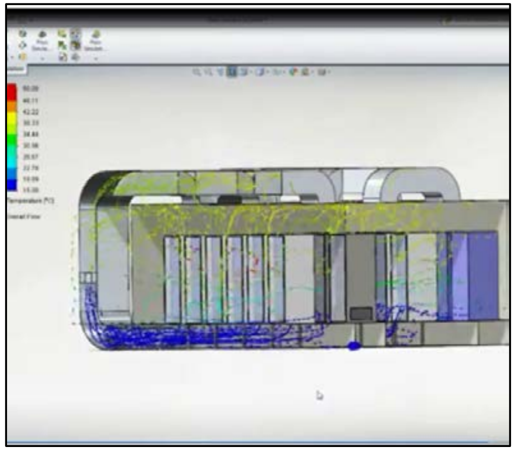

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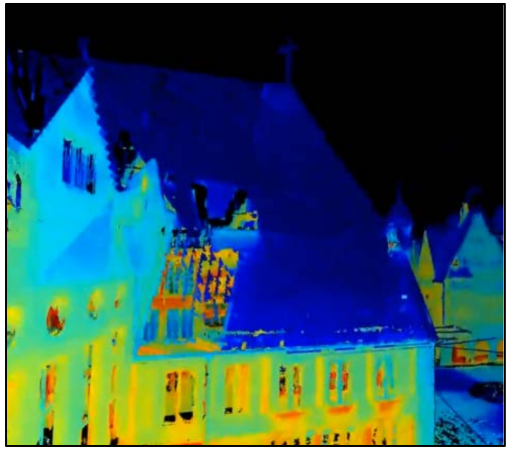
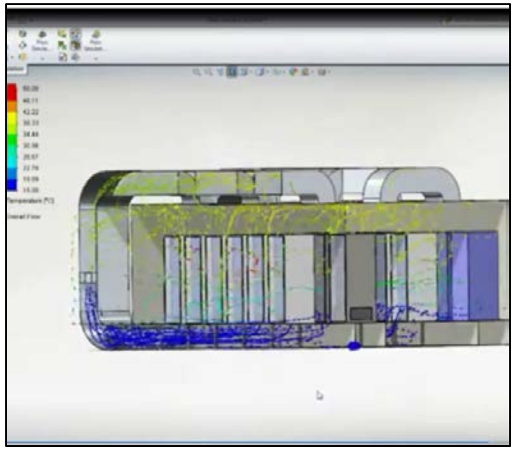


Assessing inaccessible areas

Scaling up data collection



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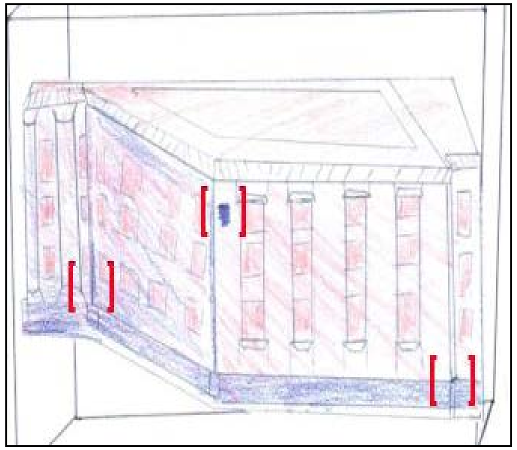
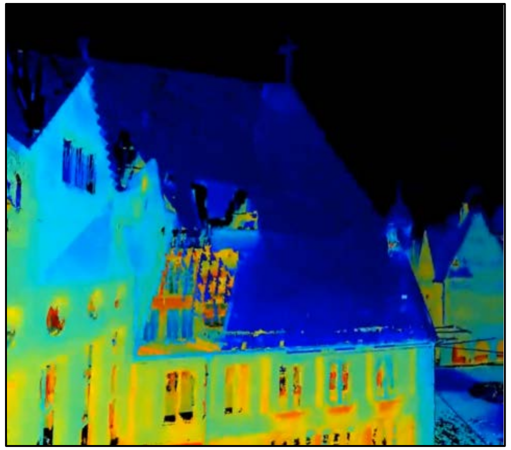


Automatic anomaly detection

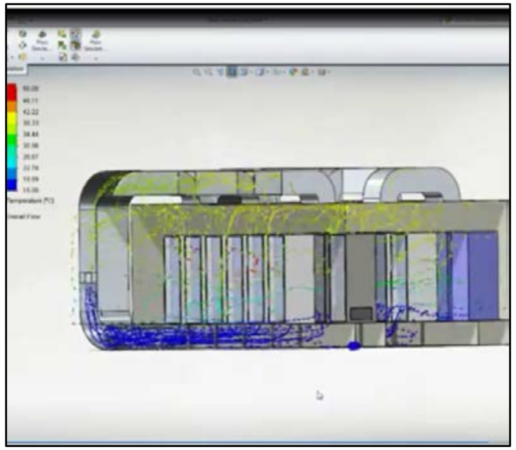
Study Findings: Design Probes, Automation Benefits

Saving time and money

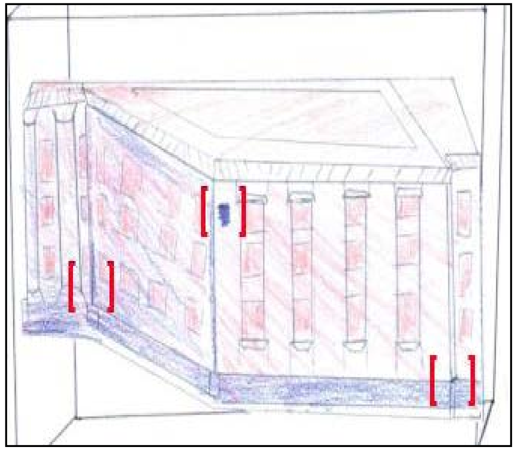


Assessing inaccessible areas

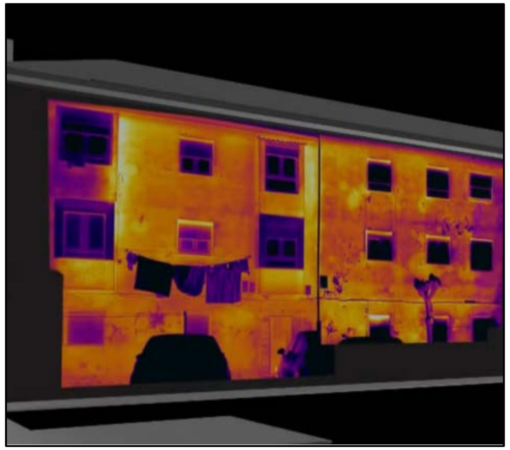
Scaling up data collection



New types of analyses



Automatic anomaly detection

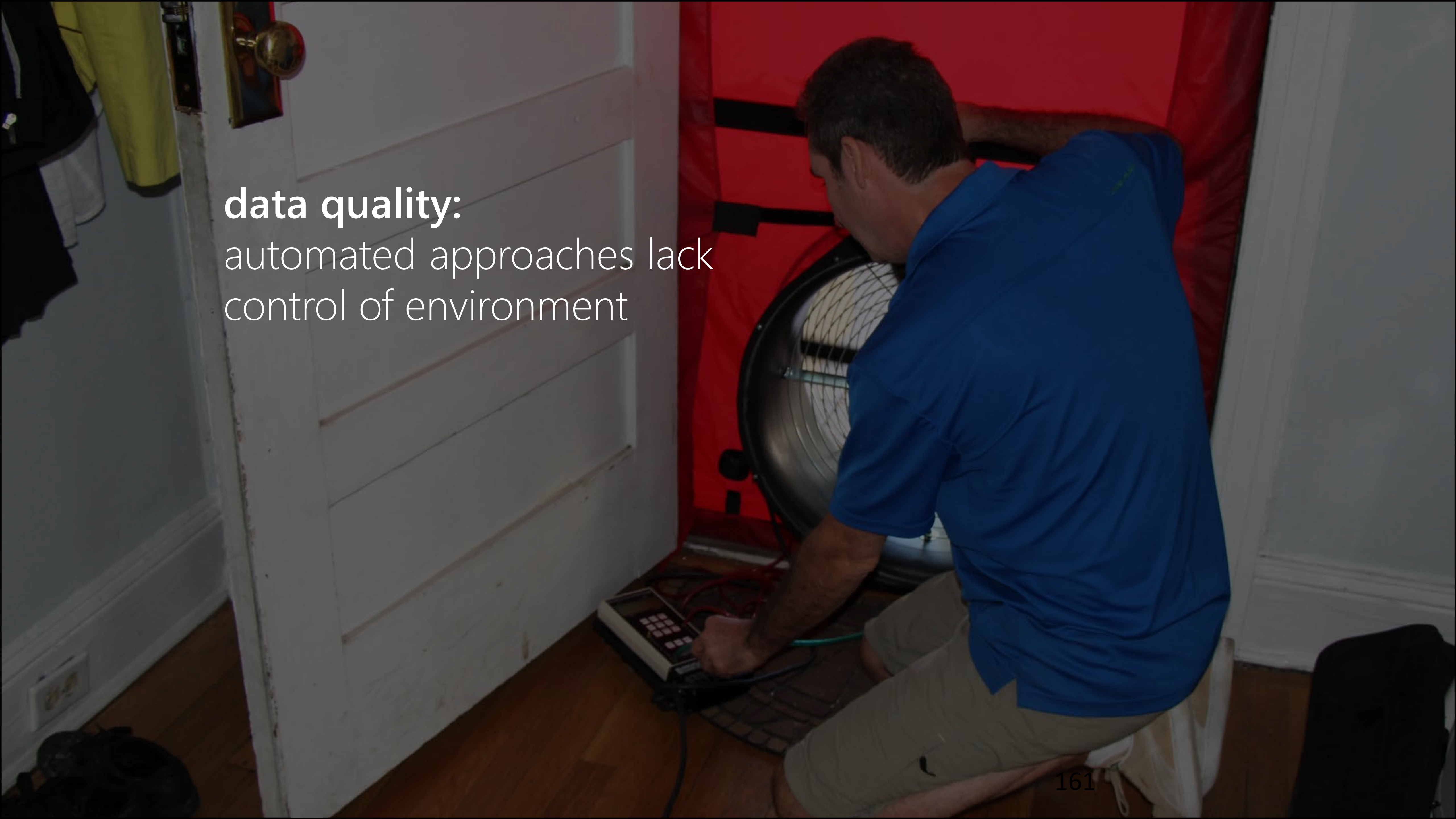


Model generation

STUDY FINDINGS: DESIGN PROBES

Automation Benefits

Concerns



data quality:
automated approaches lack control of environment

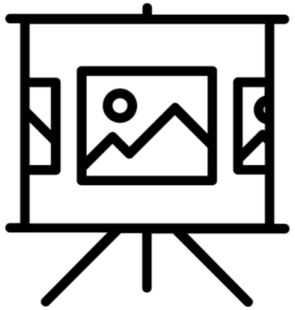
data overload:
how to manage orders of magnitude more data?

social process:
energy auditing is a
socio-technical process

STUDY METHOD: THREE-PARTS

Study 1

Part 1:
Semi-Structured Interviews
~50 Minutes



Part 2:
Presentation of Design Probes
~40 Minutes

Study 2

Observational Case Study:
Residential Energy Audit
~120 Minutes

Professional Thermograpy Study: Research Outcomes

- An assessment of **professional energy auditing** and **thermography's role therein.**

- A critical **examination of emerging automated thermographic solutions** to data collection and analysis.

- A set of **design recommendations for future** energy auditing and **thermographic tools** intended for professional use.

THREAD 2 TAKEAWAYS: PROFESSIONAL THERMOGRAPHY STUDIES

Thermography in energy auditing is serves as a subjective diagnostic and communication tool:

- Limited time for analysis

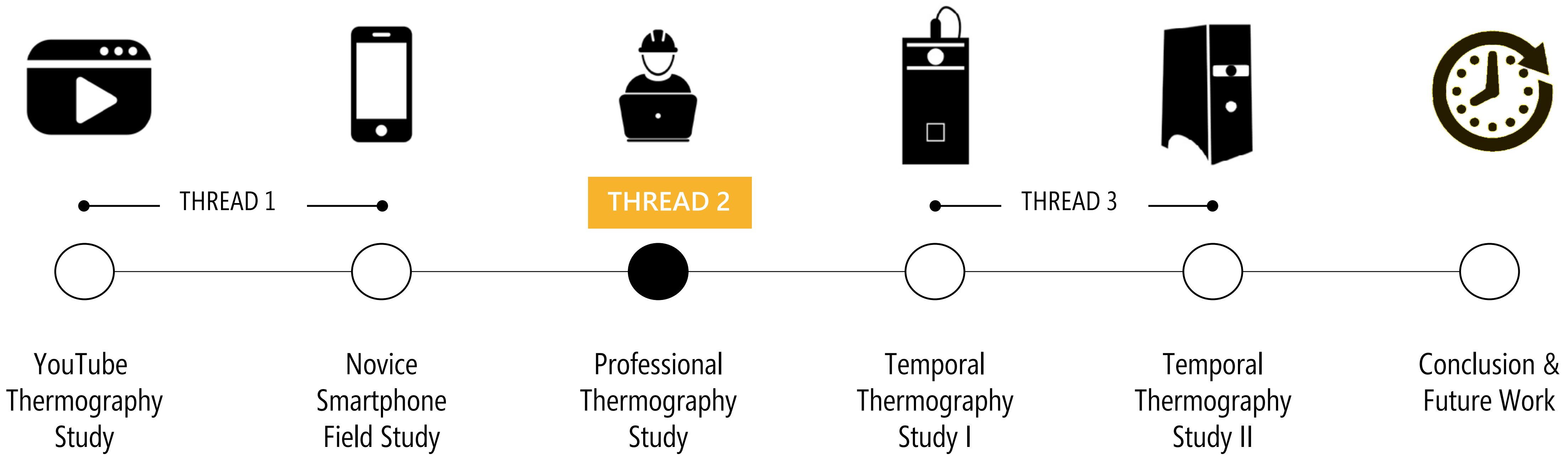
Potential benefits of automation include:

- Reducing laboriousness of data collection
- Integration of quantitative and temporal analysis

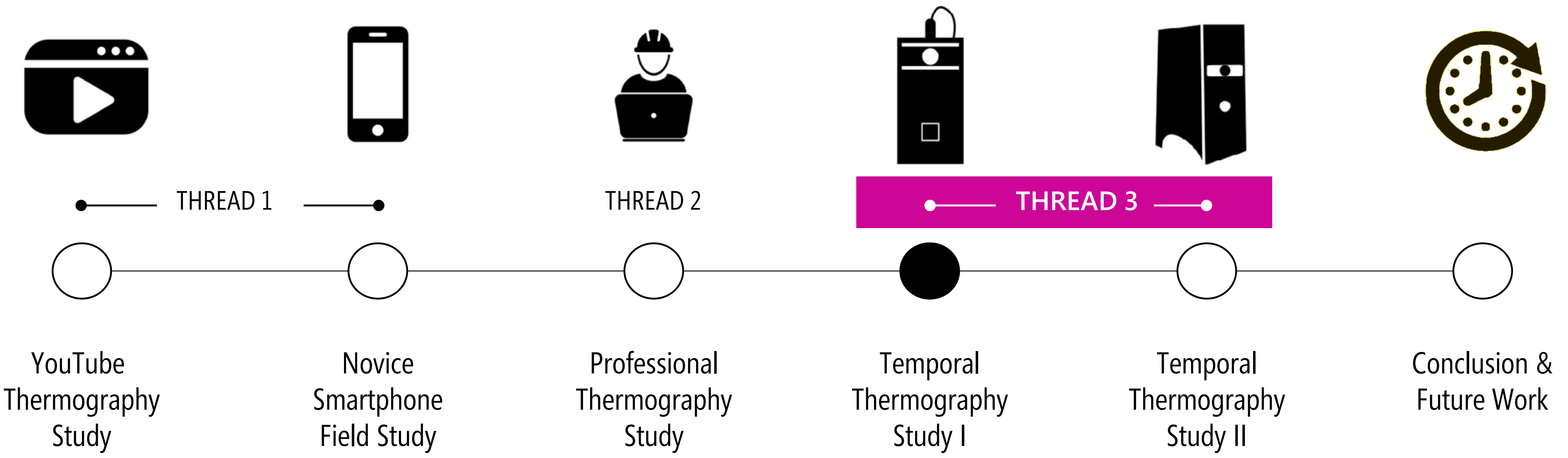
Major concerns about automation include:

- Data overload

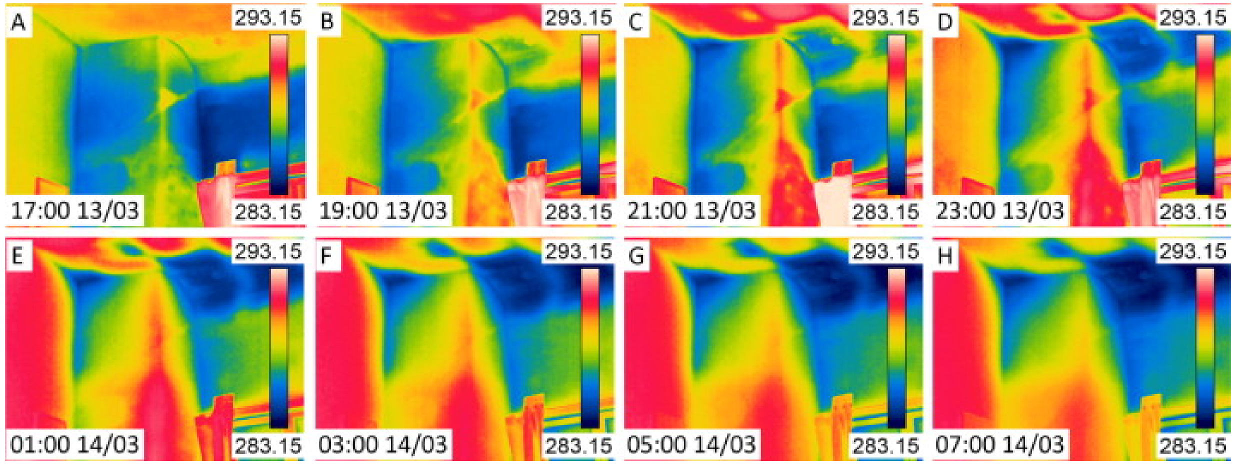
Dissertation Overview

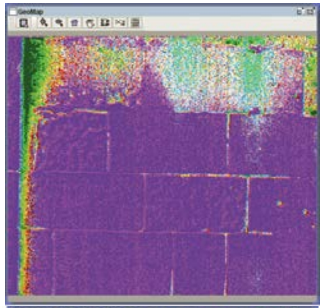


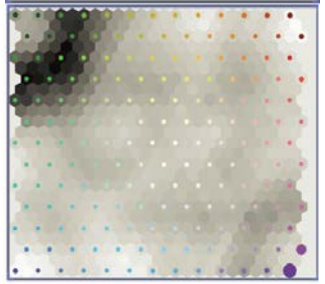
DISSERTATION OVERVIEW

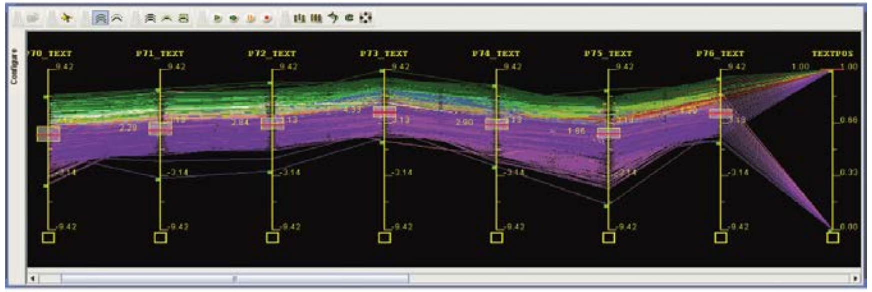


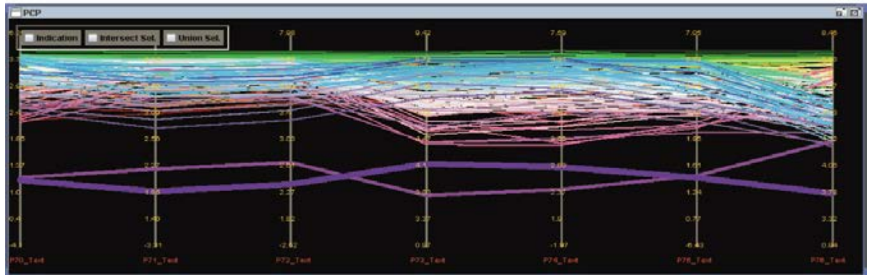
Related Work: Temporal Visualizations











Energy and Buildings 92 (2015) 95–106
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journal homepage: www.elsevier.com/locate/enbuild

Time-lapse thermography for building defect detection

Matthew Fox[a,*], David Coley[b], Steve Goodhew[a], Pieter De Wilde[a]
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Time-lapse thermography
Transient behaviour
Defect detection

1. Introduction

According to the United ... buildings account for over ... Within the European conte... EU dwellings responsible f... in buildings [2]. Of the 22... 90% were built prior to 19... ing trend throughout Eur... England for 2013 only to... government to meet carb... by 2050 [5] appears unac... to thermally improve ... energy costs are leadi... The risk of fuel pover... rural buildings [7] du...

Archaeometry 52, 3 (2010) 482–501
doi: 10.1111/j.1475-4754.2009.00485.x

INVESTIGATING MATERIAL DECAY OF HISTORIC BUILDINGS USING VISUAL ANALYTICS WITH MULTI-TEMPORAL INFRARED THERMOGRAPHIC DATA*

MARIA DANESE,[1,3] URŠKA DEMŠAR,[2]† NICOLA MASINI,[1] and MARTIN CHARLTON[2]
[1]Institute for Archaeological and Monumental Heritage (CNR-IBAM), Area di Ricerca di Potenza, C. da S. Loja, 85050 Tito Scalo (PZ), Italy
[2]National Centre for Geocomputation, National University of Ireland Maynooth, Maynooth, Co. Kildare, Ireland
[3]Urban and Territorial Systems of Engineering Laboratory, Università degli studi della Basilicata, Potenza, Italy

This paper shows how visual analytics methodology can be used to facilitate interpretation of multi-temporal thermographic imagery for the purpose of restoration of cultural heritage. We explore thermographic data in a visual environment from the unifying spatio-temporal perspective in an attempt to identify spatial and spatio-temporal patterns that could provide information about the structure and the level of decay of the material, and the presence of other physical phenomena in the wall. The approach is tested on a thermographic dataset captured on the façade of a Romanesque building from the 13th century—the Cathedral in Matera (Italy).

KEYWORDS: VISUAL ANALYTICS, MICRO-SCALE SPATIO-TEMPORAL ANALYSIS, MULTI-TEMPORAL INFRARED THERMOGRAPHY, MATERIAL DECAY AND CHARACTERIZATION, NON-DESTRUCTIVE PASSIVE TESTING, CULTURAL HERITAGE RESTORATION

INTRODUCTION

Infrared thermography (IRT) or thermal imaging is a technique used in various fields of application, such as to test thermal efficiency in buildings and to map building defects such as thermal bridges (Rosina and Robison 2002), to discover air leaks, moist spots and the location of electrical installations (Grinzato et al. 1998) and the research of hidden structure (Grinzato et al. 2002). During the past decade IRT has become very important in cultural heritage restoration and there are many recent works published on this topic. One of the main areas of research is the analysis of material decay in buildings of cultural or historical importance (Grinzato et al. 1994, 1997, 1998, 2002; Vavilov et al. 1997; Meola and Carlomagno 2004). IRT is used during all phases of restoration, from preliminary analysis to monitoring and management of results (Rosina and Robison 2002).

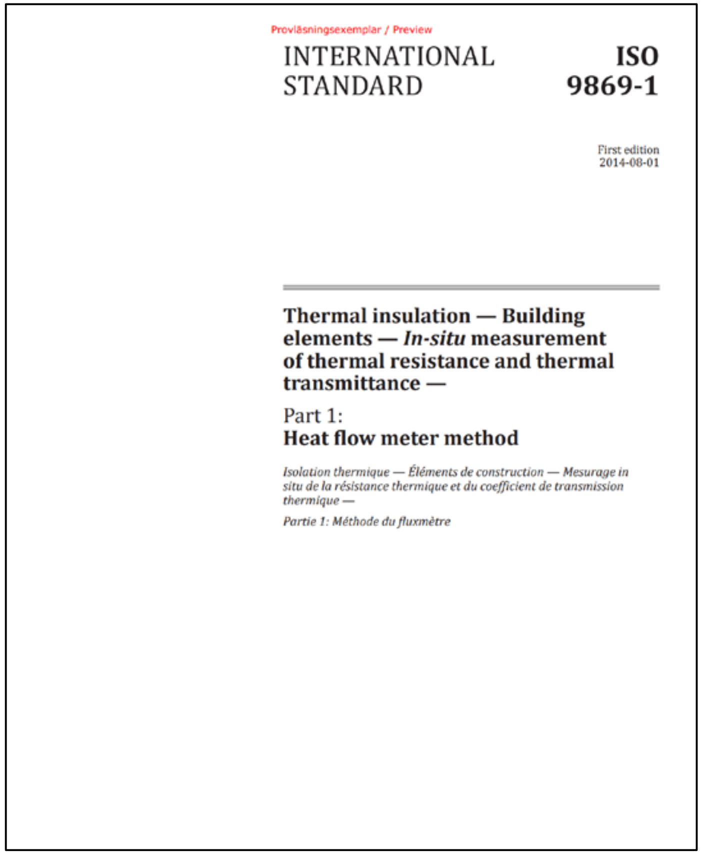
The traditional way to study multi-temporal IR images is also the simplest: we construct a profile of the temperature variations that tells us about thermal inertia. However, thermal datasets are typically very large, which means that multi-temporal and spatial patterns in the data that could tell us more about the thermal behaviour and properties of the materials are difficult to identify. In this paper we propose the use of visual analytics methodology to facilitate identification of such patterns. The proposed approach was also tested in an experimental exploration of an infrared thermographic dataset captured on a façade of a historical building.

*Received 5 December 2008; accepted 2 April 2009

†Corresponding author: email: urska.demsar@nuim.ie

RELATED WORK: QUANTITATIVE MEASUREMENT

Direct Contact Methods:
Heat Flux Sensors and Thermocouples
(~72 Hour Measurement Time)


Provläsningsexemplar / Preview

INTERNATIONAL STANDARD **ISO 9869-1**

First edition
2014-08-01

Thermal insulation — Building elements — *In-situ* measurement of thermal resistance and thermal transmittance —

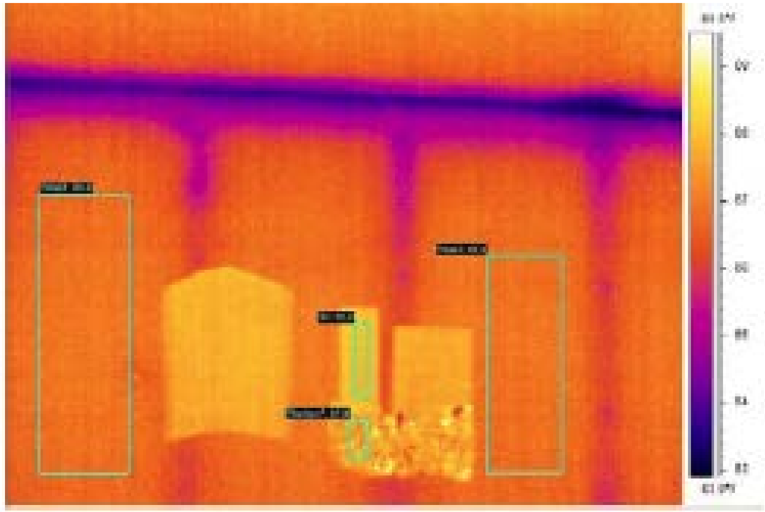
Part 1:
Heat flow meter method

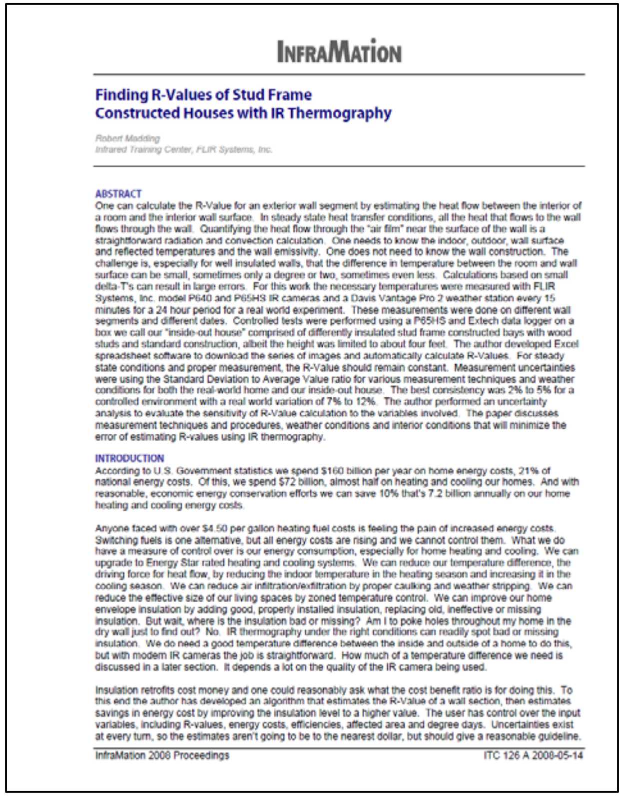
Isolation thermique — Éléments de construction — Mesurage in situ de la résistance thermique et du coefficient de transmission thermique —

Partie 1: Méthode du fluxmètre

Current Standard

Related Work: Quantitative Thermography





InfraMation

Finding R-Values of Stud Frame Constructed Houses with IR Thermography

Robert Madding
Infrared Training Center, FLIR Systems, Inc.

ABSTRACT
One can calculate the R-Value for an exterior wall segment by estimating the heat flow between the interior of a room and the interior wall surface. In steady state heat transfer conditions, all the heat that flows to the wall flows through the wall. Quantifying the heat flow through the "air film" near the surface of the wall is a straightforward radiation and convection calculation. One needs to know the indoor, outdoor, wall surface and reflected temperatures and the wall emissivity. One does not need to know the wall construction. The challenge is, especially for well insulated walls, that the difference in temperature between the room and wall surface can be small, sometimes only a degree or two, sometimes even less. Calculations based on small delta-T's can result in large errors. For this work the necessary temperatures were measured with FLIR Systems, Inc. model P640 and P65HS IR cameras and a Davis Vantage Pro 2 weather station every 15 minutes for a 24 hour period for a real world experiment. These measurements were done on different wall segments and different dates. Controlled tests were performed using a P65HS and Extech data logger on a box we call our "inside-out house" comprised of differently insulated stud frame constructed bays with wood studs and standard construction, albeit the height was limited to about four feet. The author developed Excel spreadsheet software to download the series of images and automatically calculate R-Values. For steady state conditions and proper measurement, the R-Value should remain constant. Measurement uncertainties were using the Standard Deviation to Average Value ratio for various measurement techniques and weather conditions for both the real-world home and our inside-out house. The best consistency was 2% to 5% for a controlled environment with a real world variation of 7% to 12%. The author performed an uncertainty analysis to evaluate the sensitivity of R-Value calculation to the variables involved. The paper discusses measurement techniques and procedures, weather conditions and interior conditions that will minimize the error of estimating R-values using IR thermography.

INTRODUCTION
According to U.S. Government statistics we spend $160 billion per year on home energy costs, 21% of national energy costs. Of this, we spend $72 billion, almost half on heating and cooling our homes. And with reasonable, economic energy conservation efforts we can save 10% that's 7.2 billion annually on our home heating and cooling energy costs.

Anyone faced with over $4.50 per gallon heating fuel costs is feeling the pain of increased energy costs. Switching fuels is one alternative, but all energy costs are rising and we cannot control them. What we do have a measure of control over is our energy consumption, especially for home heating and cooling. We can upgrade to Energy Star rated heating and cooling systems. We can reduce our temperature difference, the driving force for heat flow, by reducing the indoor temperature in the heating season and increasing it in the cooling season. We can reduce air infiltration/exfiltration by proper caulking and weather stripping. We can reduce the effective size of our living spaces by zoned temperature control. We can improve our home envelope insulation by adding good, properly installed insulation, replacing old, ineffective or missing insulation. But wait, where is the insulation bad or missing? Am I to poke holes throughout my home in the dry wall just to find out? No. IR thermography under the right conditions can readily spot bad or missing insulation. We do need a good temperature difference between the inside and outside of a home to do this, but with modern IR cameras the job is straightforward. How much of a temperature difference we need is discussed in a later section. It depends a lot on the quality of the IR camera being used.

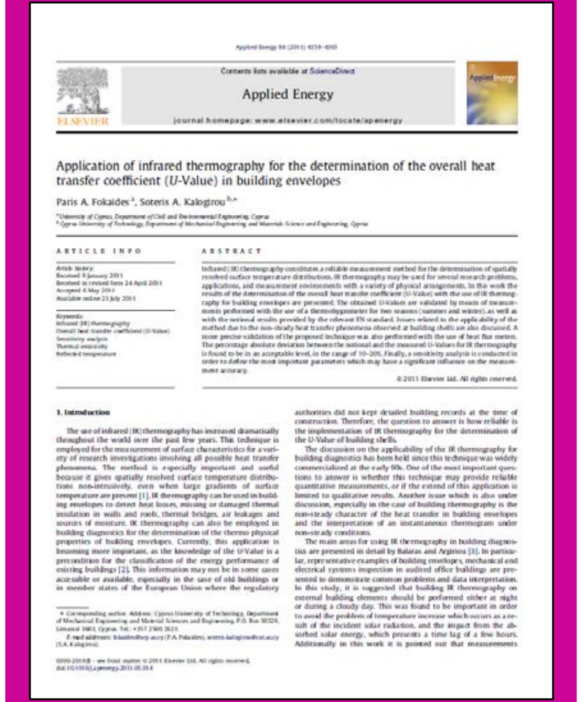
Insulation retrofits cost money and one could reasonably ask what the cost benefit ratio is for doing this. To this end the author has developed an algorithm that estimates the R-Value of a wall section, then estimates savings in energy cost by improving the insulation level to a higher value. The user has control over the input variables, including R-values, energy costs, efficiencies, affected area and degree days. Uncertainties exist at every turn, so the estimates aren't going to be to the nearest dollar, but should give a reasonable guideline.

InfraMation 2008 Proceedings ITC 126 A 2008-05-14

$$R-Value=\frac{\Delta T_{io}}{4\varepsilon\sigma T_m{}^3\Delta T_r+h_c\Delta T_a}$$

Madding 2008

Related Work: Quantitative Temporal Thermography

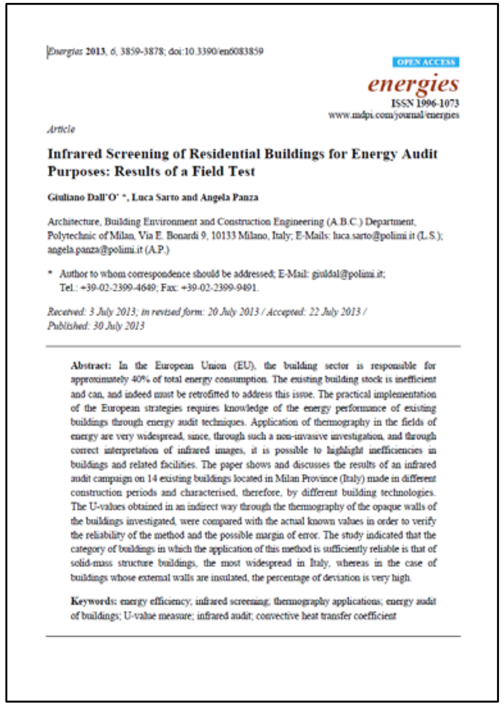


Applied Energy

Application of infrared thermography for the determination of the overall heat transfer coefficient (U-Value) in building envelopes

Paris A. Fokaides, Soteris A. Kalogirou

Fokaides & Kalogirou, 2011



Energies 2013, 6, 3859-3878; doi:10.3390/en6083859

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ISSN 1996-1073

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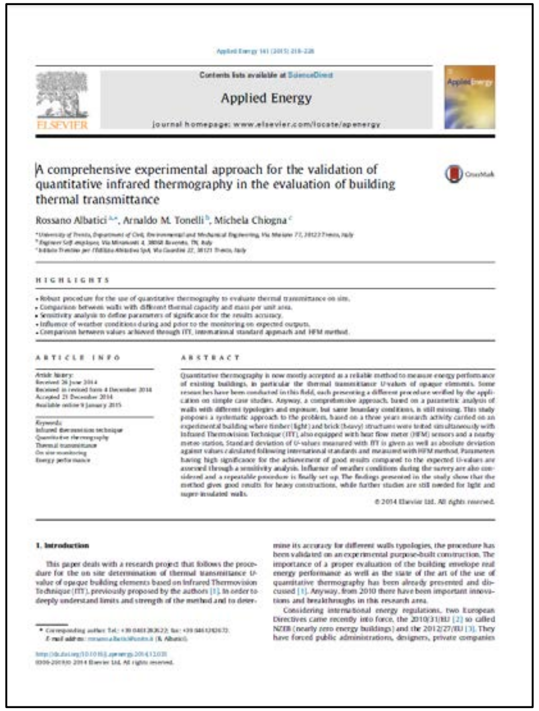
Article

Infrared Screening of Residential Buildings for Energy Audit Purposes: Results of a Field Test

Giuliano Dall'O' *, Luca Sarto and Angela Panza

Dall'O *et al.*, 2013



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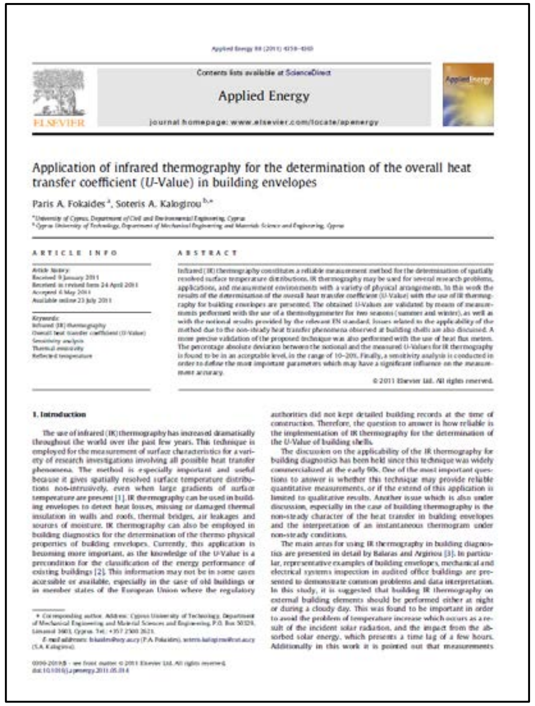
U-value assessment by infrared thermography: A comparison of different calculation methods in a Guarded Hot Box

Iole Nardi, Domenica Paoletti, Dario Ambrosini, Tullio de Rubeis, Stefano Sfarra

Nardi *et al.*, 2016

Related Work: Quantitative Temporal Thermography



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Article

Infrared Screening of Residential Buildings for Energy Audit Purposes: Results of a Field Test

Giuliano Dall'O' *, Luca Sarto and Angela Panza

Architecture, Built Environment and Construction Engineering (A.B.C.) Department, Polytechnic of Milan, Via E. Bonardi 9, 10133 Milano, Italy; E-Mails: luca.sarto@polimi.it (L.S.); angela.panza@polimi.it (A.P.)

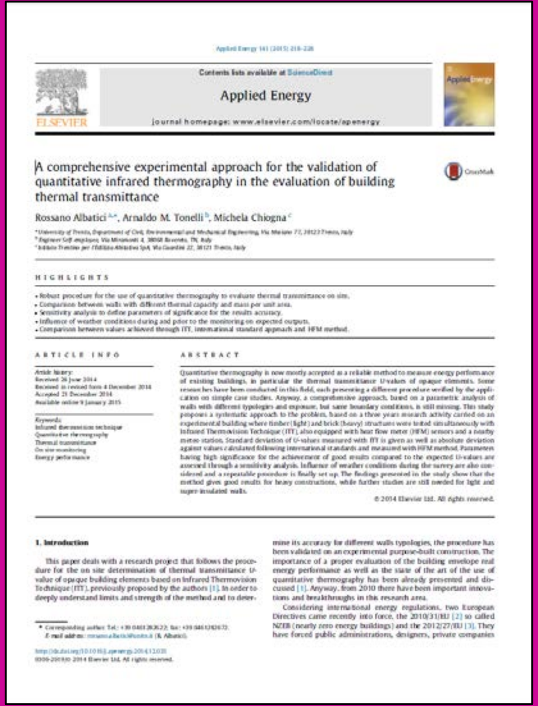
* Author to whom correspondence should be addressed; E-Mail: giuldal@polimi.it; Tel.: +39-02-2399-4649; Fax: +39-02-2399-9491.

Received: 3 July 2013; in revised form: 20 July 2013 / Accepted: 22 July 2013 / Published: 30 July 2013

Abstract: In the European Union (EU), the building sector is responsible for approximately 40% of total energy consumption. The existing building stock is inefficient and can, and indeed must be retrofitted to address this issue. The practical implementation of the European strategies requires knowledge of the energy performance of existing buildings through energy audit techniques. Application of thermography in the fields of energy are very widespread, since, through such a non-invasive investigation, and through correct interpretation of infrared images, it is possible to highlight inefficiencies in buildings and related facilities. The paper shows and discusses the results of an infrared audit campaign on 14 existing buildings located in Milan Province (Italy) made in different construction periods and characterised, therefore, by different building technologies. The U-values obtained in an indirect way through the thermography of the opaque walls of the buildings investigated, were compared with the actual known values in order to verify the reliability of the method and the possible margin of error. The study indicated that the category of buildings in which the application of this method is sufficiently reliable is that of solid-mass structure buildings, the most widespread in Italy, whereas in the case of buildings whose external walls are insulated, the percentage of deviation is very high.

Keywords: energy efficiency; infrared screening; thermography applications; energy audit of buildings; U-value measure; infrared audit; convective heat transfer coefficient

Dall'O *et al.*, 2013



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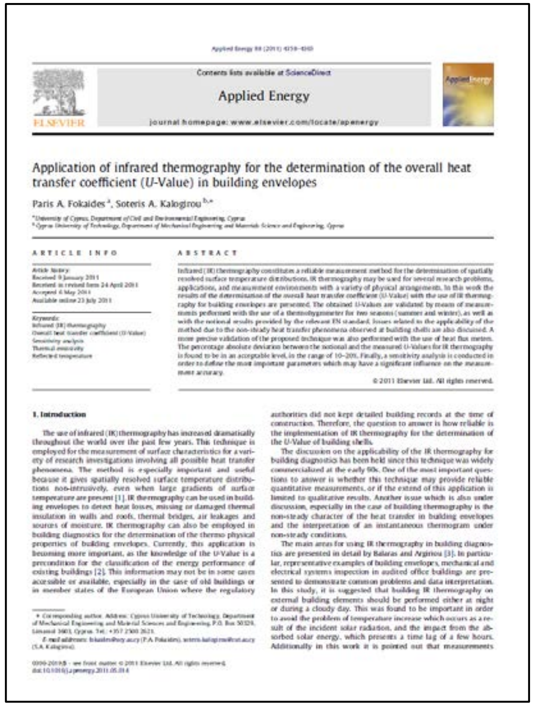
Nardi *et al.*, 2016

RELATED WORK: QUANTITATIVE TEMPORAL THERMOGRAPHY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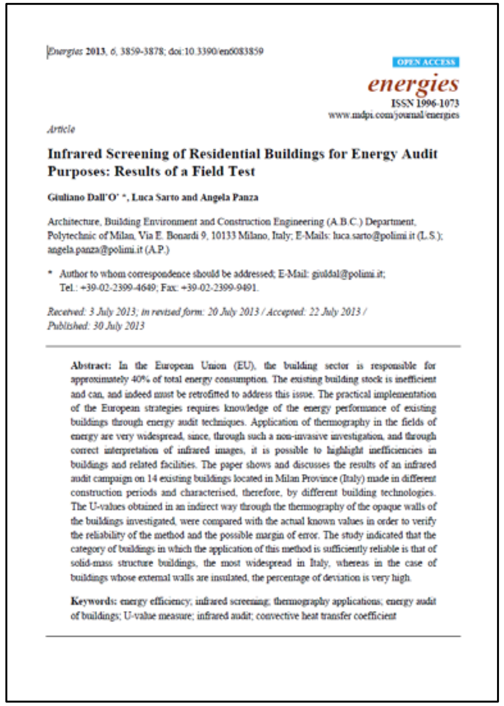
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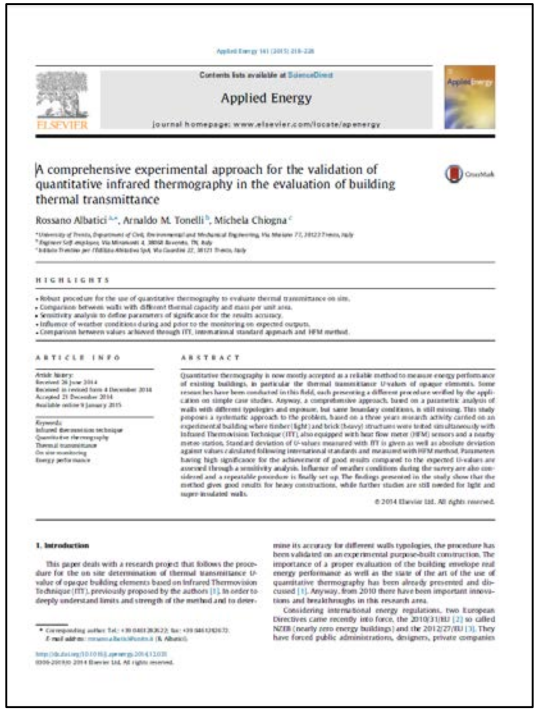
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Nardi *et al.*, 2016

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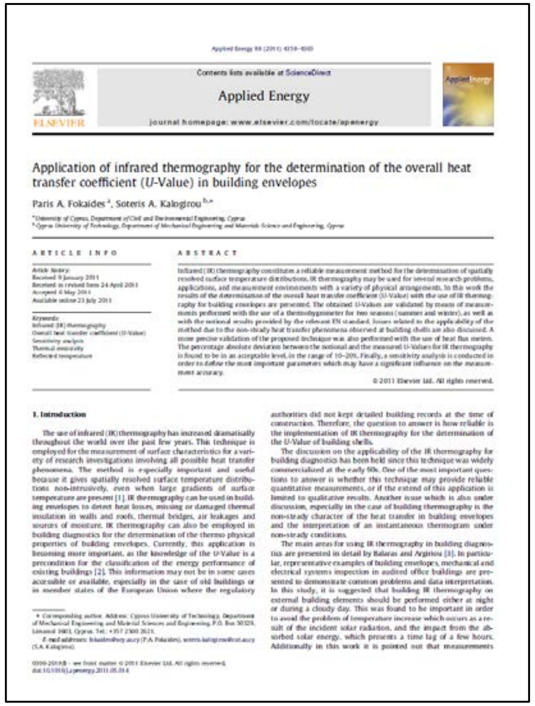
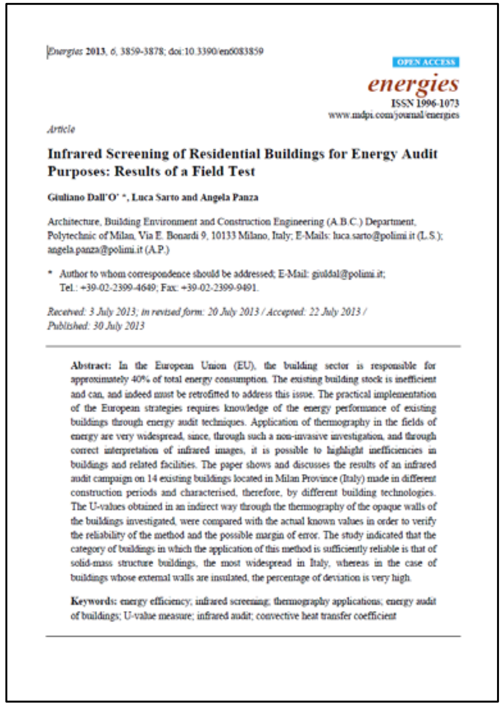
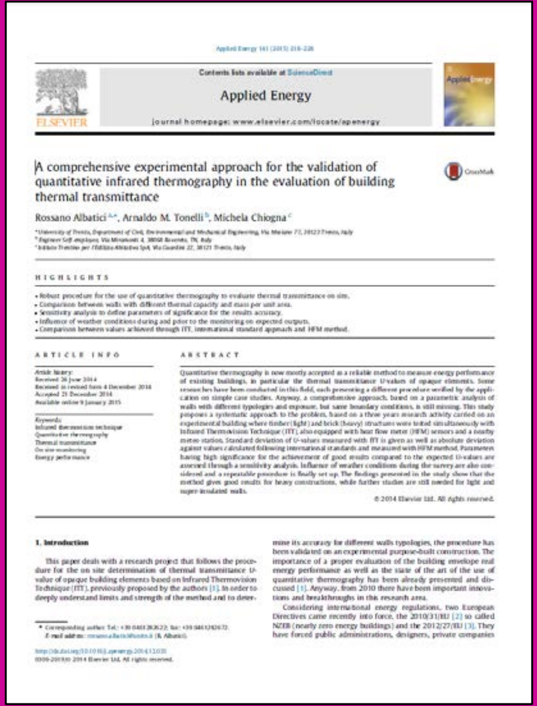


Fokaides & Kalogirou, 2011



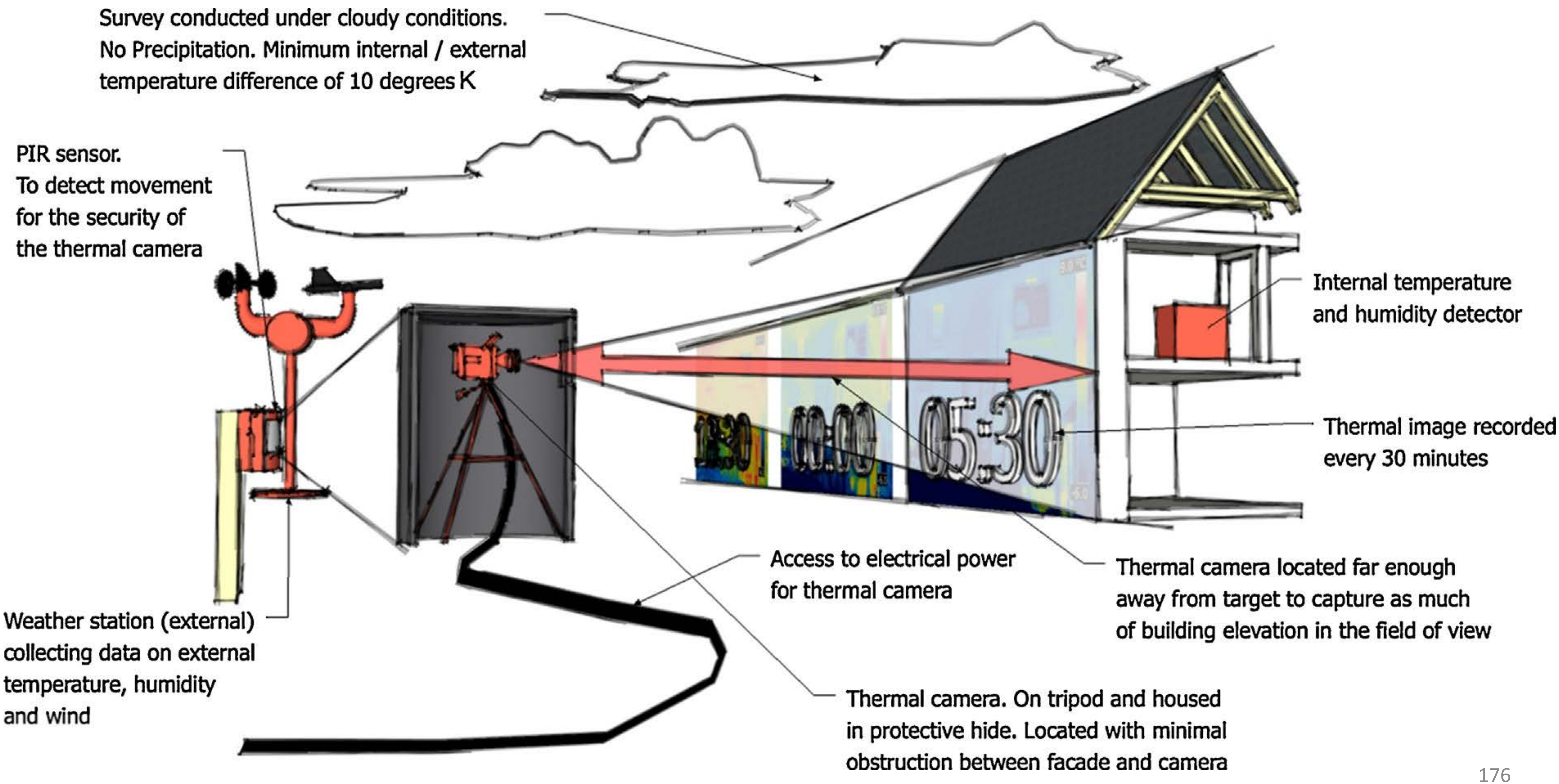
Dall'O *et al.*, 2013



Albatici *et al.*, 2015

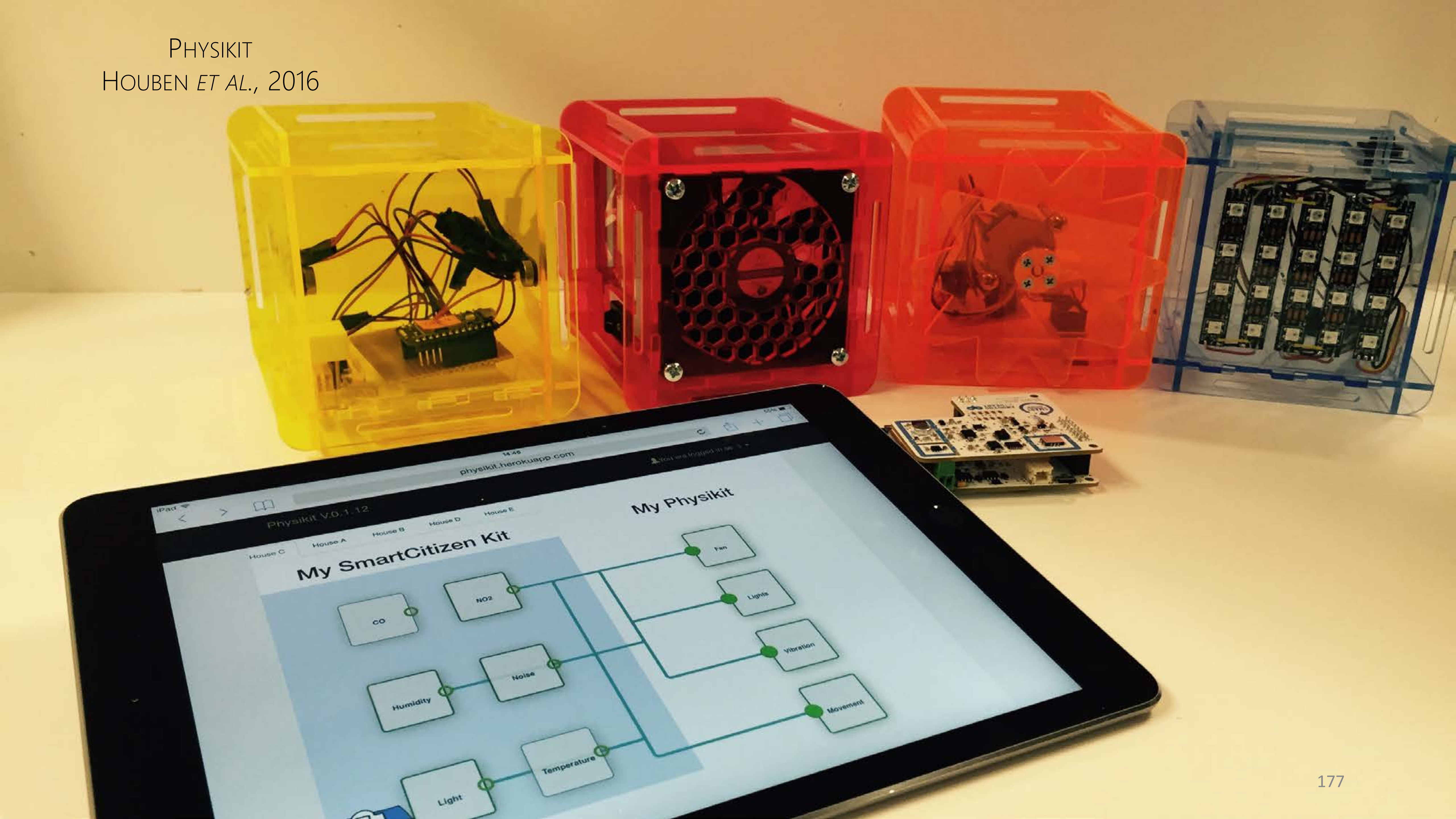
Nardi *et al.*, 2016

Related Work: Temporal Data Collection



PHYSIKIT

HOUBEN *ET AL.*, 2016



PHYSIKIT
HOUBEN *ET AL.*, 2016

BuildAX Environmental Sensor Toolkit
Finnigan *et al.* 2017

PHYSIKIT
HOUBEN *ET AL.*, 2016

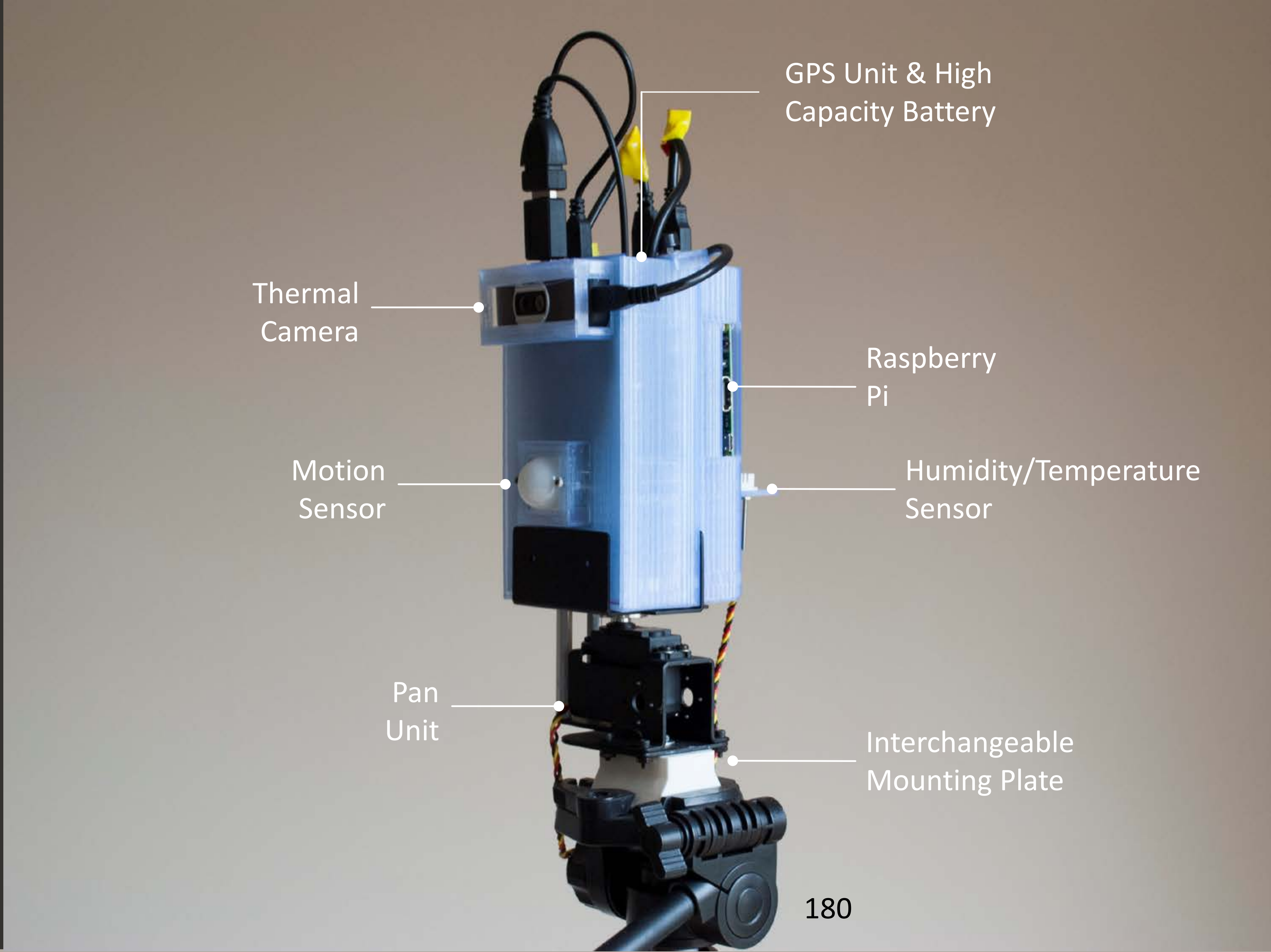
TEMPORAL THERMOGRAPHY STUDY I: RESEARCH QUESTIONS

1. What value and insights, if any, does temporal thermography provide energy auditors?

2. How might temporal thermography be incorporated into residential building energy audits?

BuildAX Environmental Sensor Toolkit
Finnigan *et al.* 2017

EASY-TO-DEPLOY THERMOGRAPHIC SENSOR SYSTEM
(v3.0)



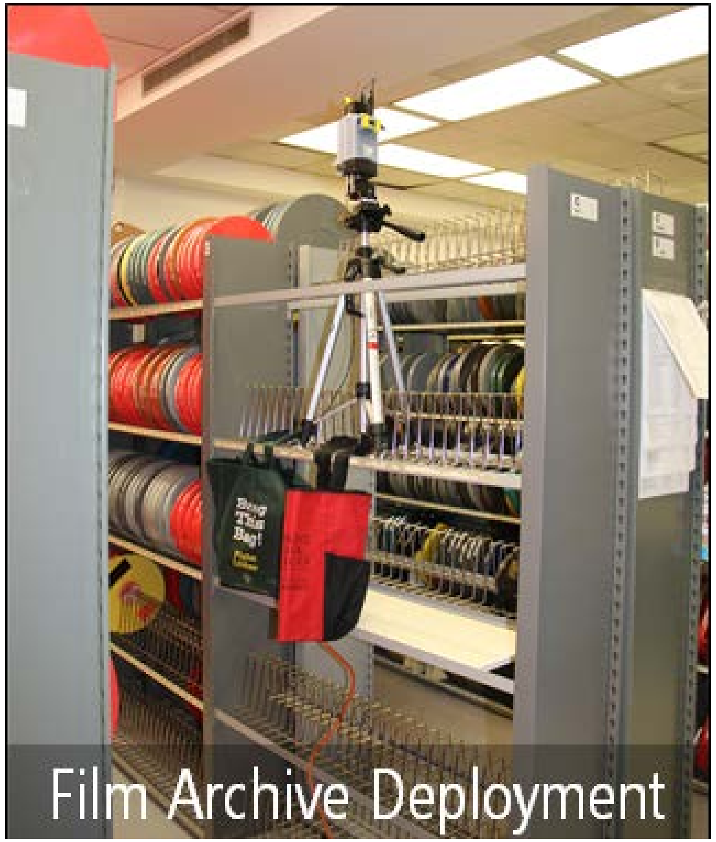
STUDY DESIGN: USABILITY STUDY METHODS

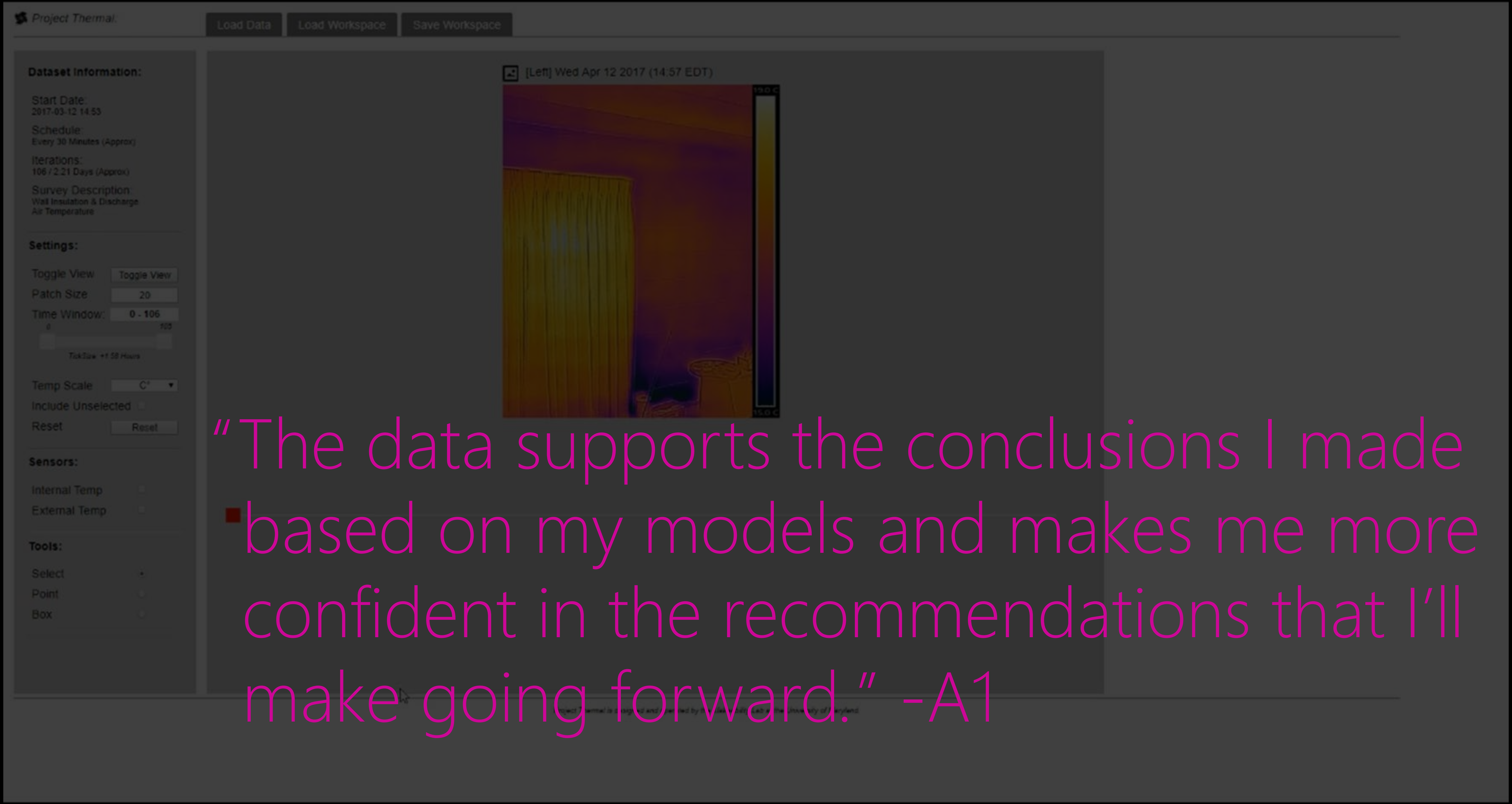
- An auditor working with the University's Department of Facilities Management deployed our system to support an energy audit in Hornbake Library.

- Data collection sessions: winter and spring.

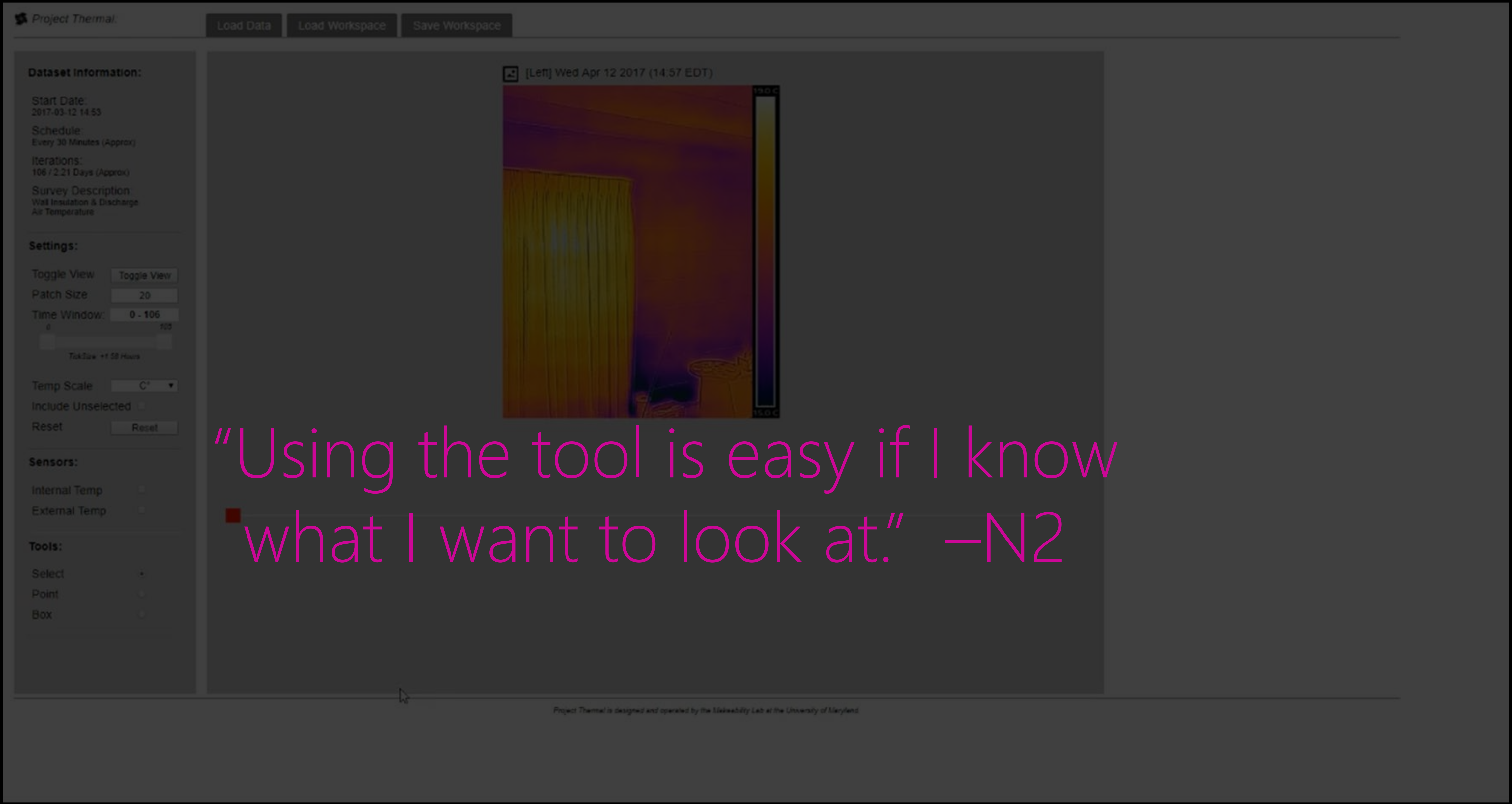
- The energy auditor used the system and provided feedback.

- Additionally, 4 graduate students provided feedback on the visualization tool using our collected datasets.





"The data supports the conclusions I made based on my models and makes me more confident in the recommendations that I'll make going forward." -A1



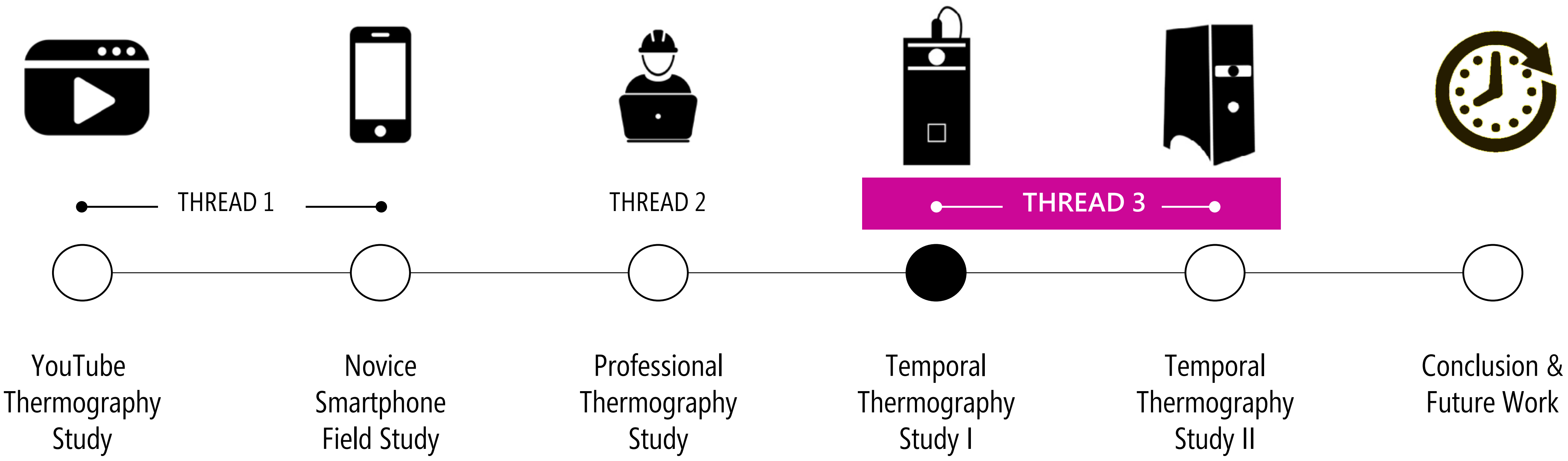
"Using the tool is easy if I know what I want to look at." –N2

TEMPORAL STUDY I: RESEARCH OUTCOMES

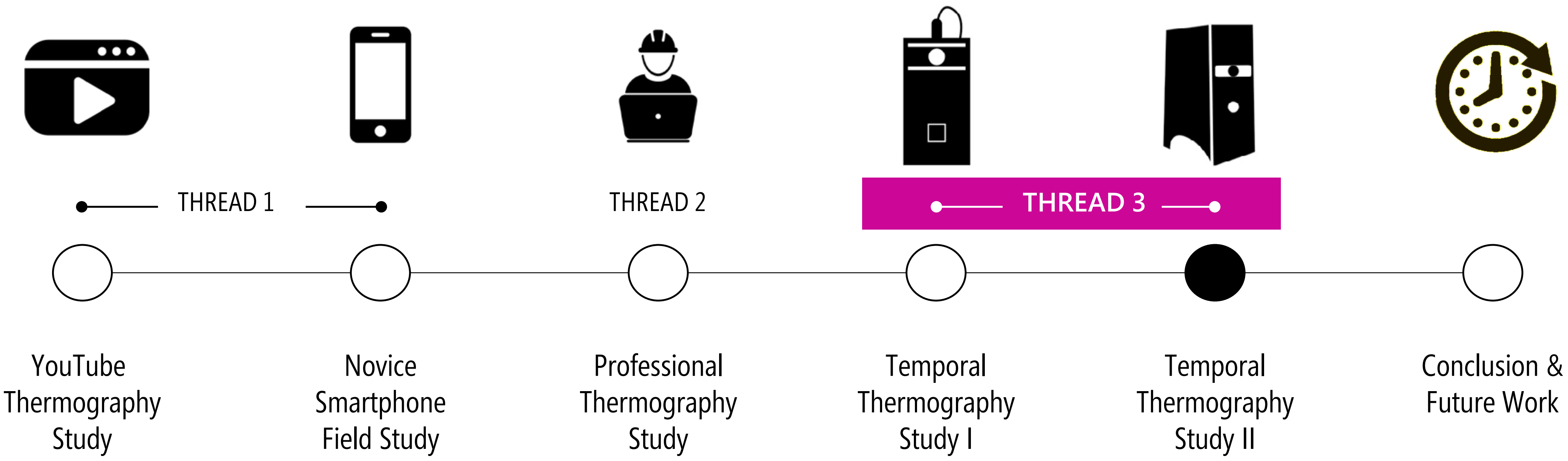
Temporal data may make identifying transient environmental conditions (*e.g.*, solar loading) easier to identify—a potential confounding variable when analyzing thermal imagery.

Without first-hand knowledge of the data collection site or a model to compare against, it may be difficult to extract additional insights from temporal datasets.

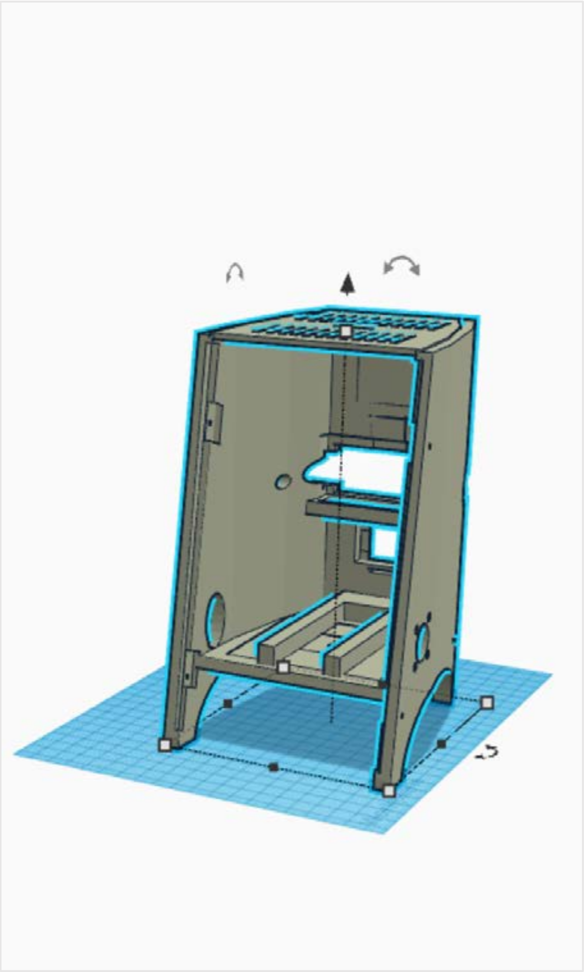
DISSERTATION OVERVIEW



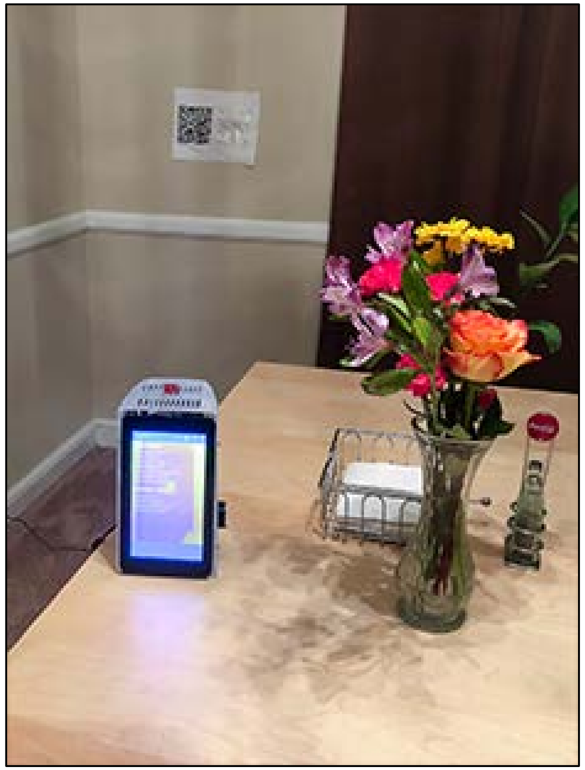
Dissertation Overview



Development: Easy-to-Deploy Thermographic Sensor Kit (v4.0)



DEVELOPMENT: SYSTEM OVERVIEW



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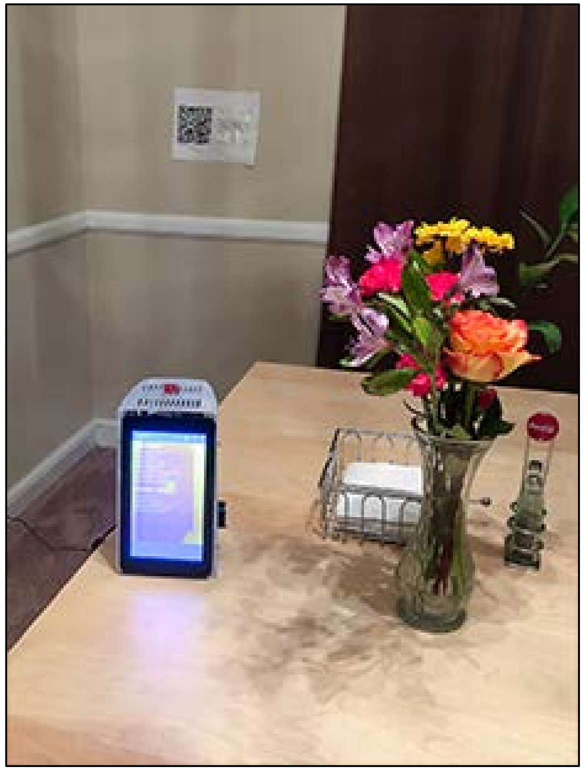

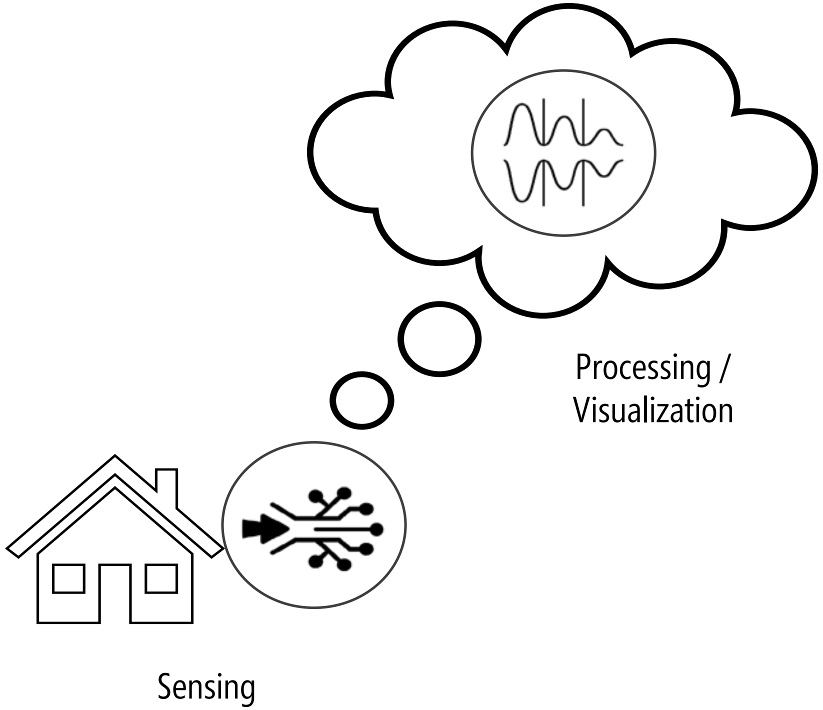

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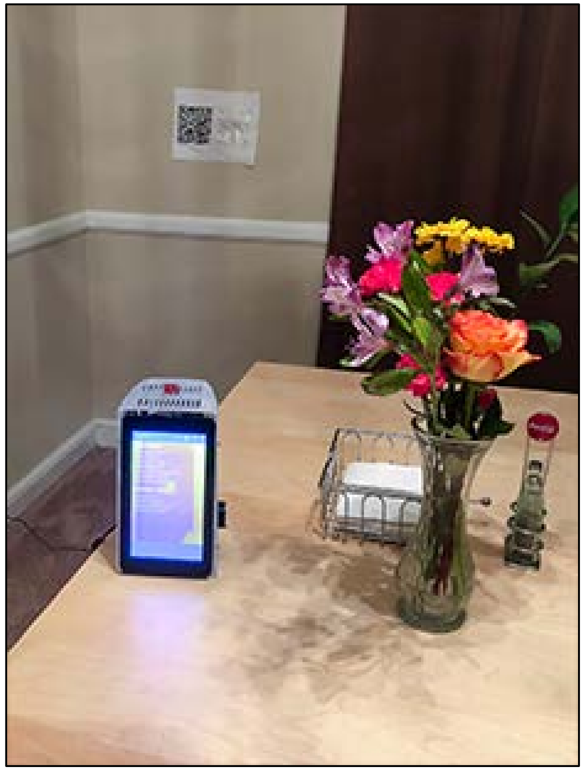
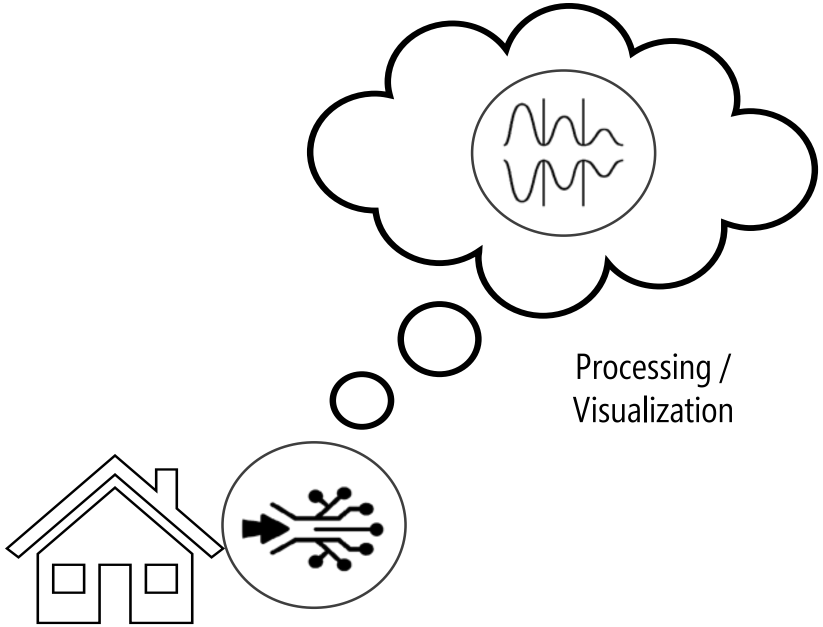
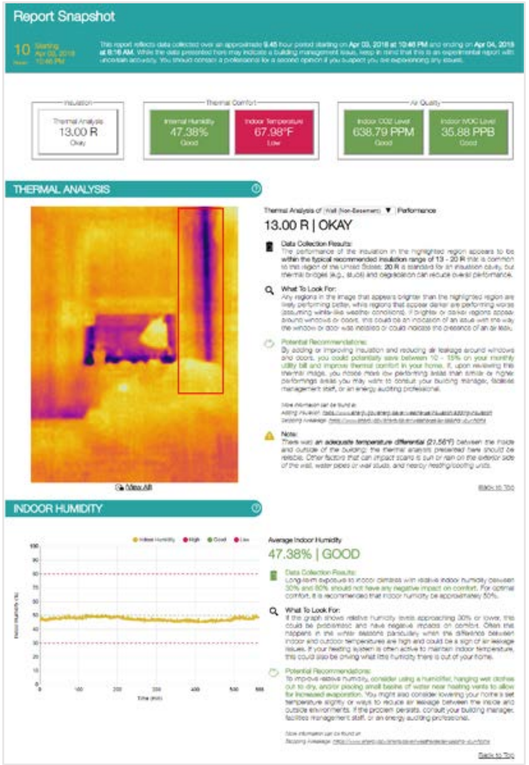


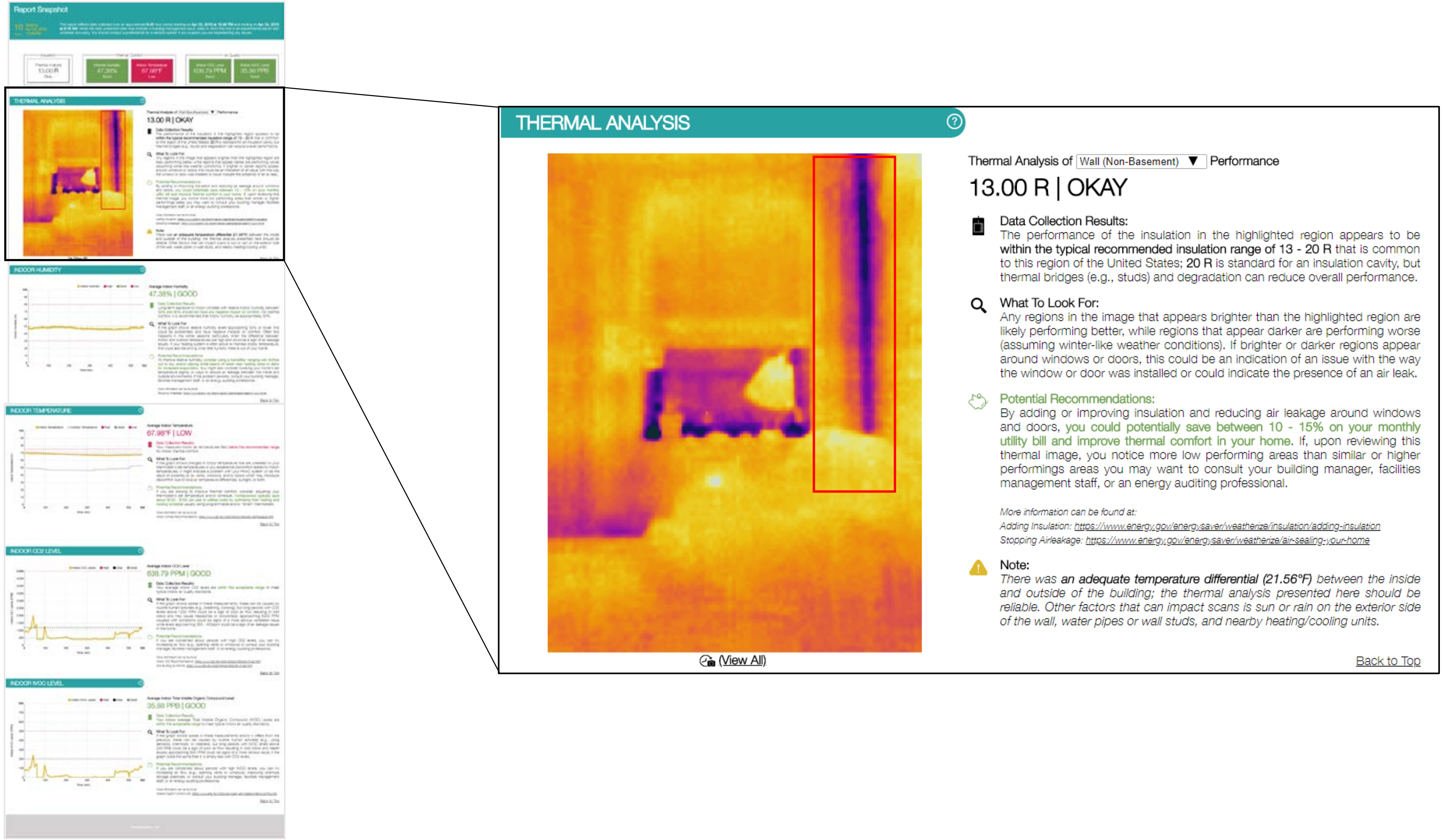


Processing / Visualization

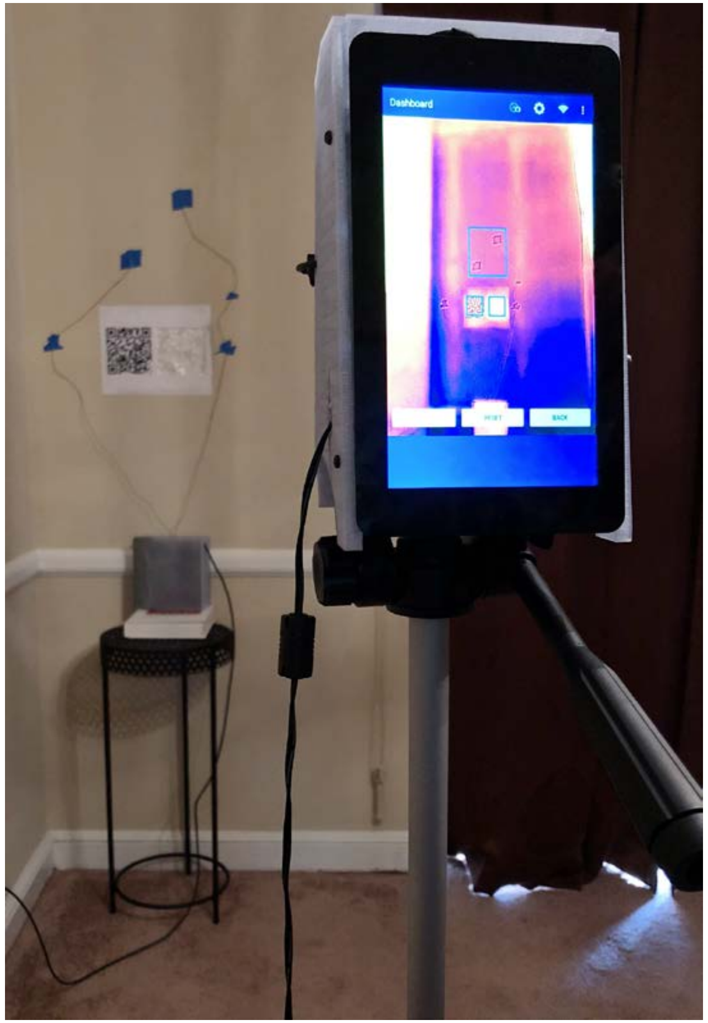
Sensing



DEVELOPMENT: REVISED VISUALIZATION



Development: Validation Experiments

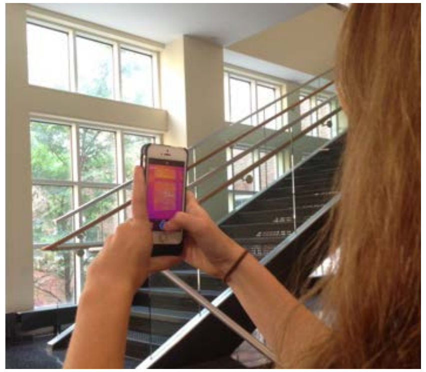


DEVELOPMENT: VALIDATION RESULTS

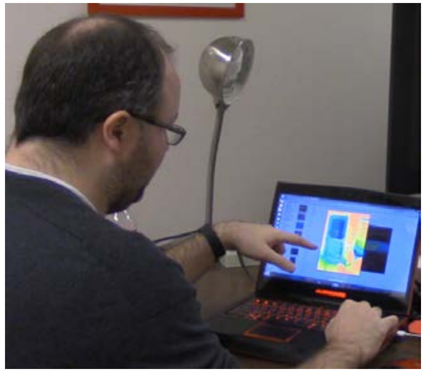
Data Segment	Notional	THM (deviation)	IRT (deviation)	Average Temp. Delta
Overnight 1	R-6.50	R-7.54 (16.00%)	R-7.67 (18.00%)	27.47°C
Overnight 2	R-6.50	R-6.67 (2.61%)	R-6.29 (3.23%)	20.96°C
Full Campaign	R-6.50	R-6.30 (3.07%)	R-6.39 (1.69%)	22.85°C

STUDY METHOD: NOVICE AND PROFESSIONAL STUDIES

Novice Study



Field Activities



Semi-Structured Interviews

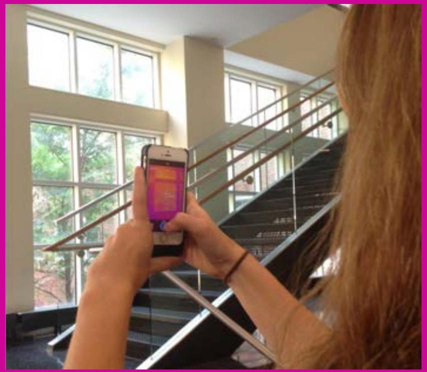
Professional Study

Part 1:
Semi-Structured Interviews

Part 2:
Presentation of Design Probes

STUDY METHOD: NOVICE AND PROFESSIONAL STUDIES

Novice Study



Field Activities

Semi-Structured Interviews

Professional Study

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Semi-Structured Interviews

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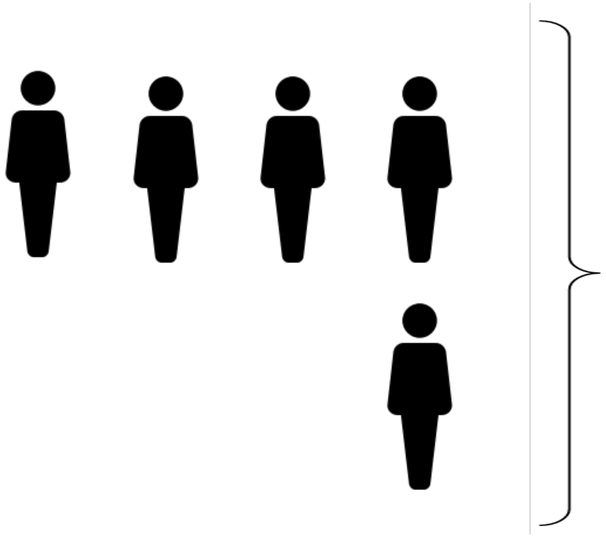
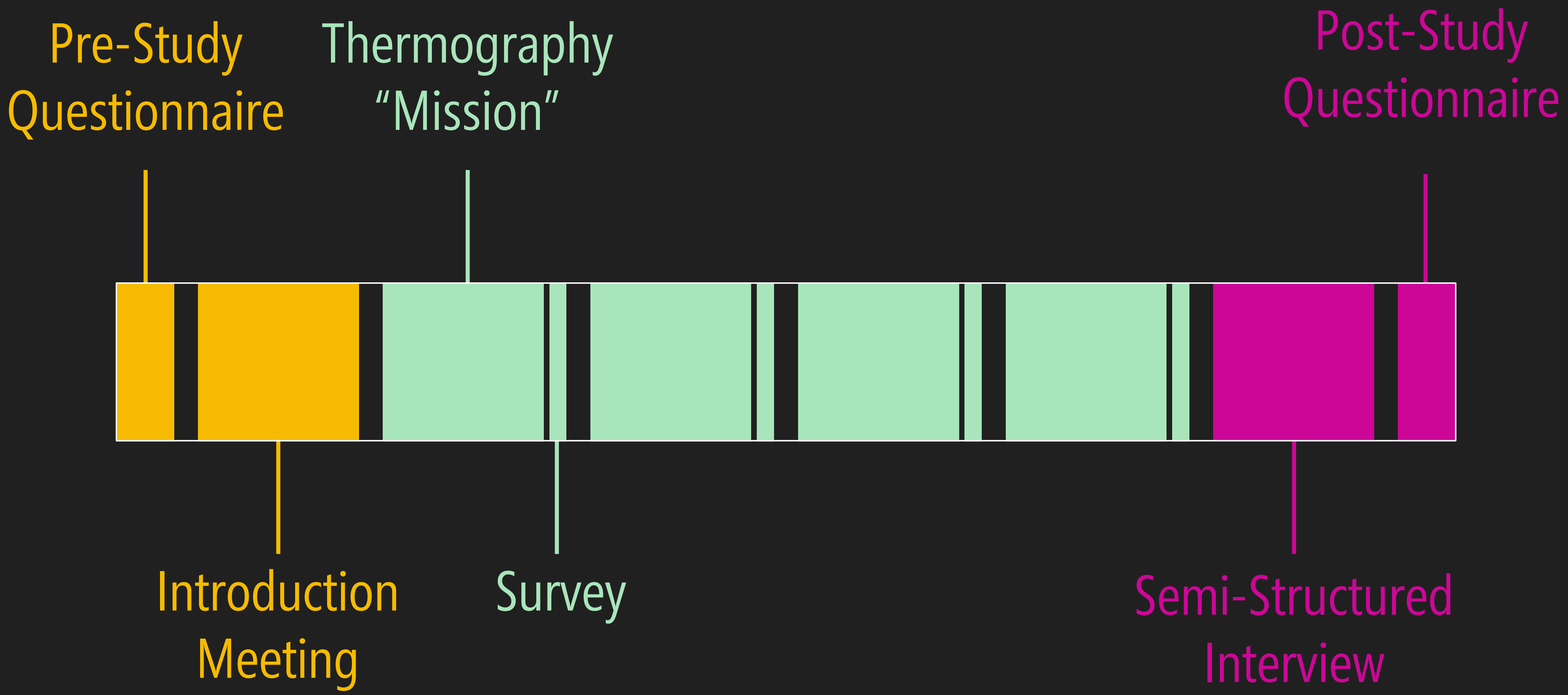
NOVICE STUDY METHOD: PARTICIPANTS

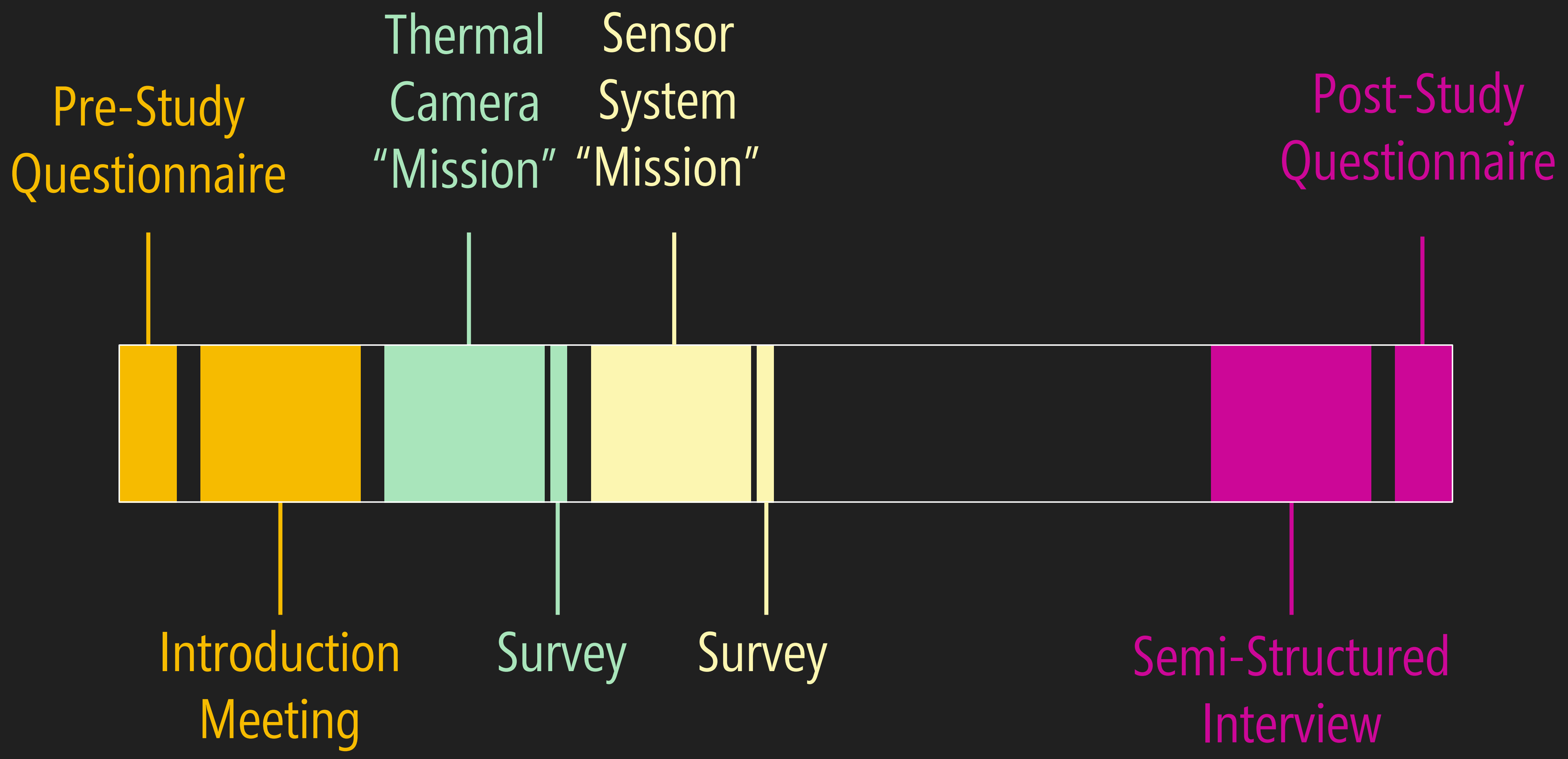


5 Participants (1 Female)

Novice Study Method: Previous Field Study Procedure



Novice Study Method: Updated Field Study Procedure



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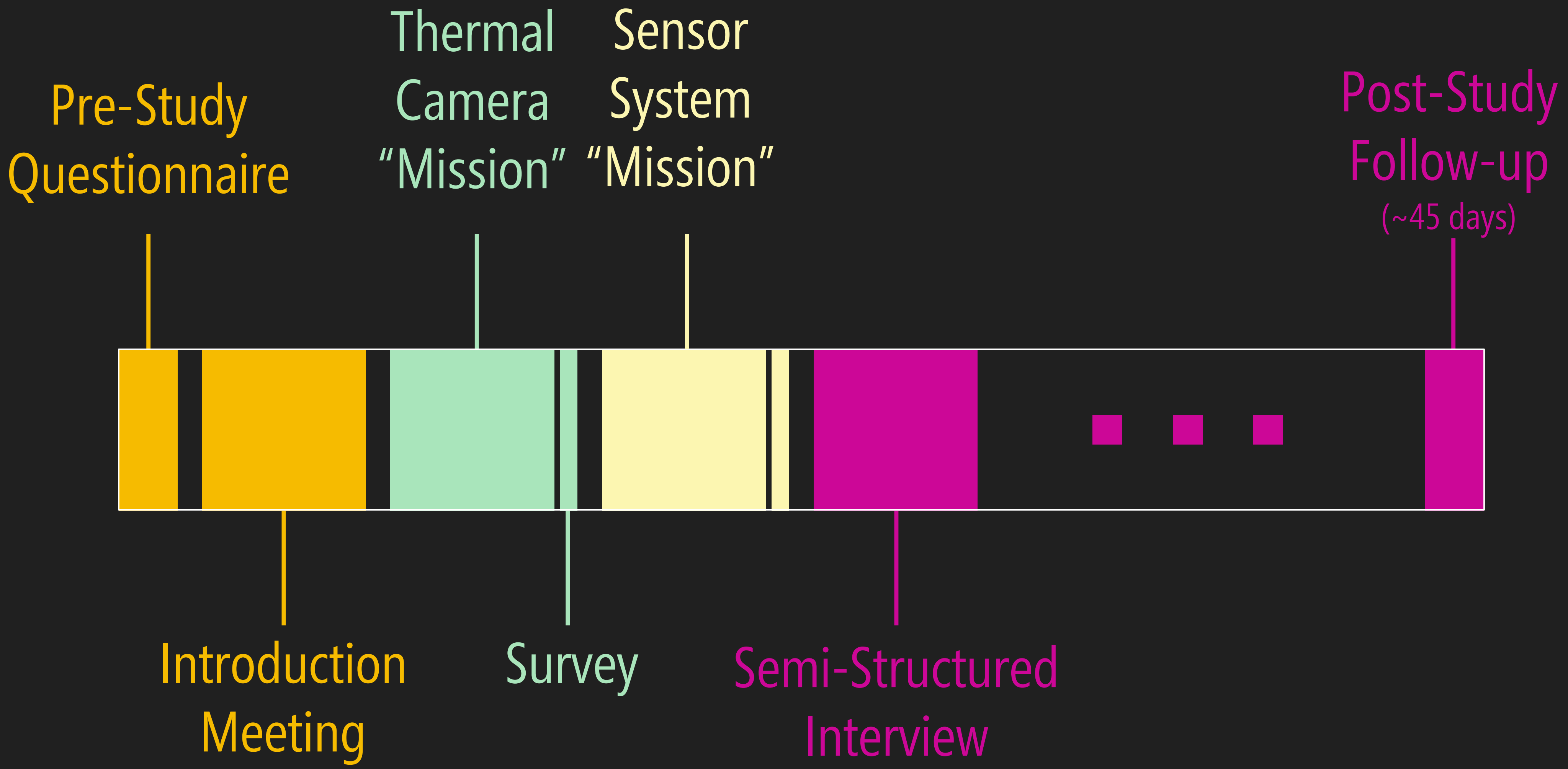
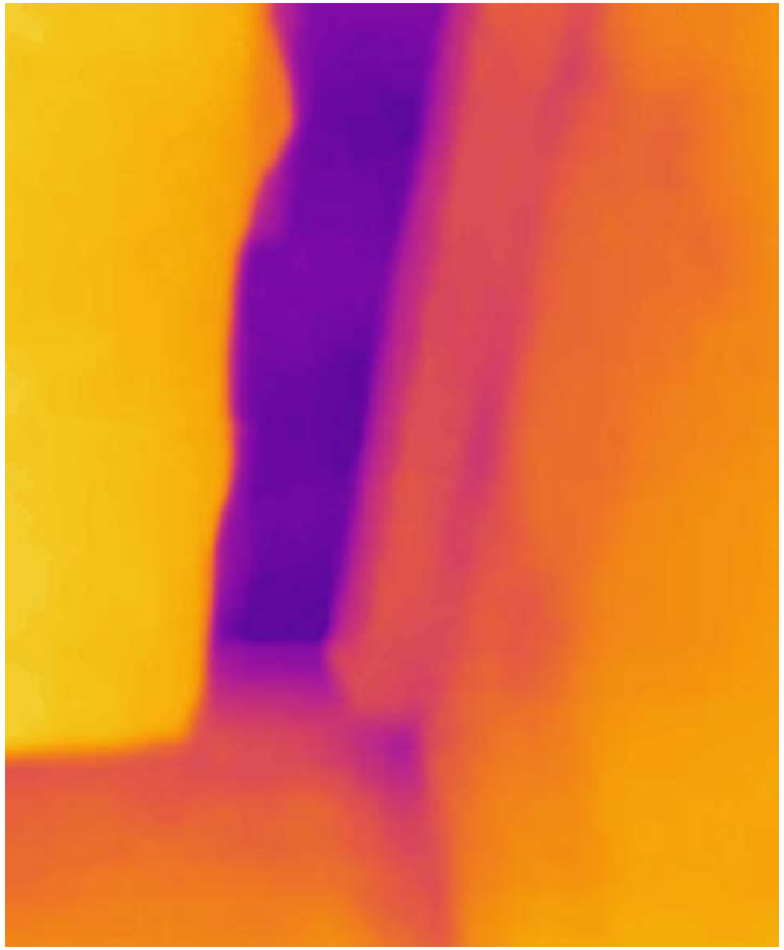
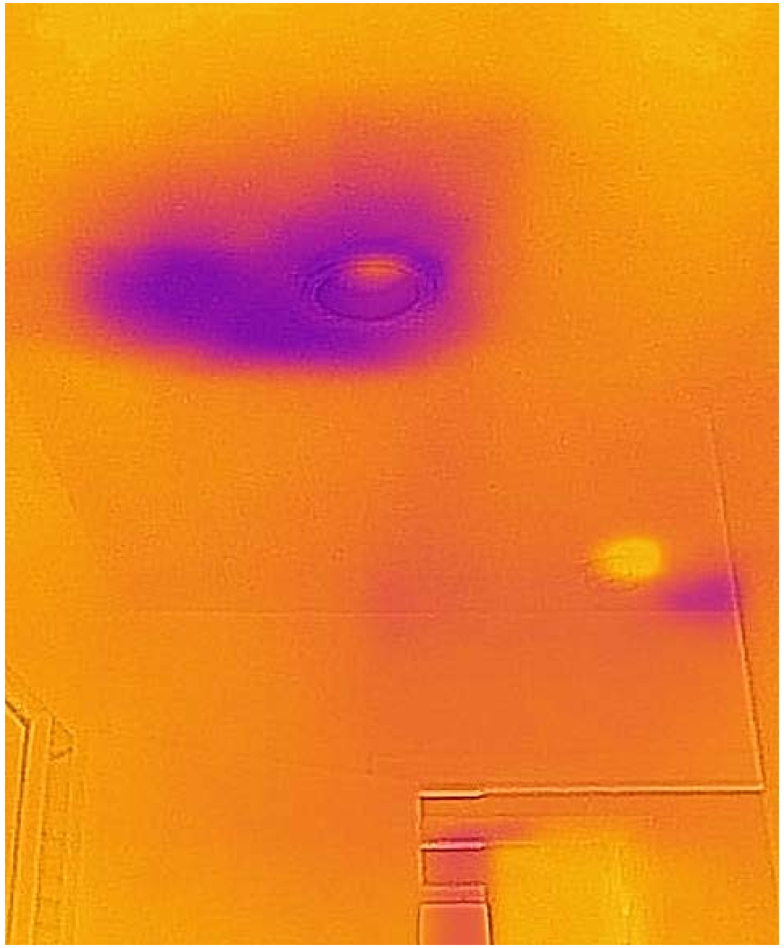
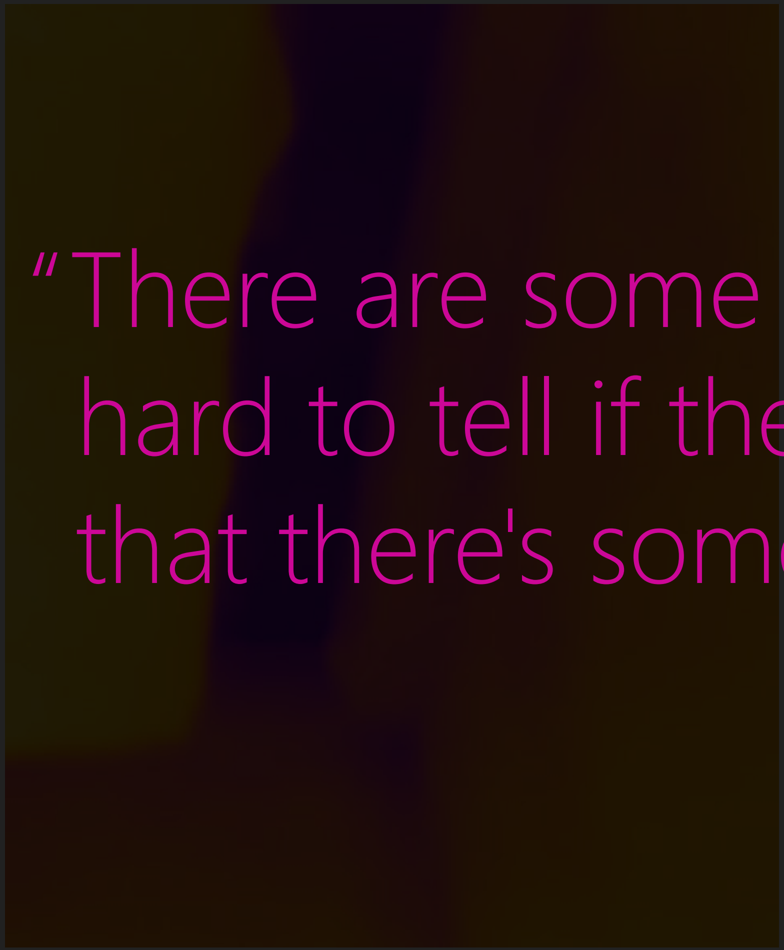


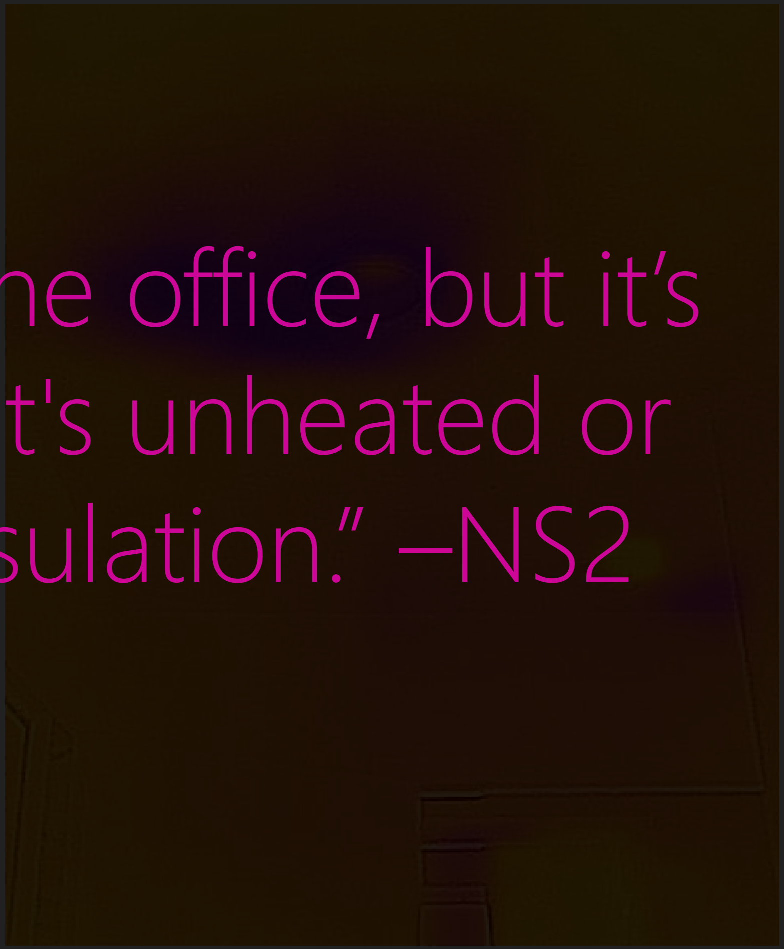
Novice Study Findings: Activity 1, Thermal Camera Findings





Novice Study Findings: Field Study Findings





"There are some very cold spots in the office, but it's hard to tell if they are just because it's unheated or that there's some big gaps in the insulation." –NS2

NOVICE STUDY FINDINGS: SENSOR SYSTEM FINDINGS

Participant ID	Sensor Kit Aimed at Suspected Issue	Issue was Found
P1	No	No
P2	Yes	Yes *Less severe than anticipated*
P3	Yes	Yes
P4	No	Yes
P5	Yes *Based on intuition, not thermal camera mission*	No

Novice Study Findings: Sensor System Findings

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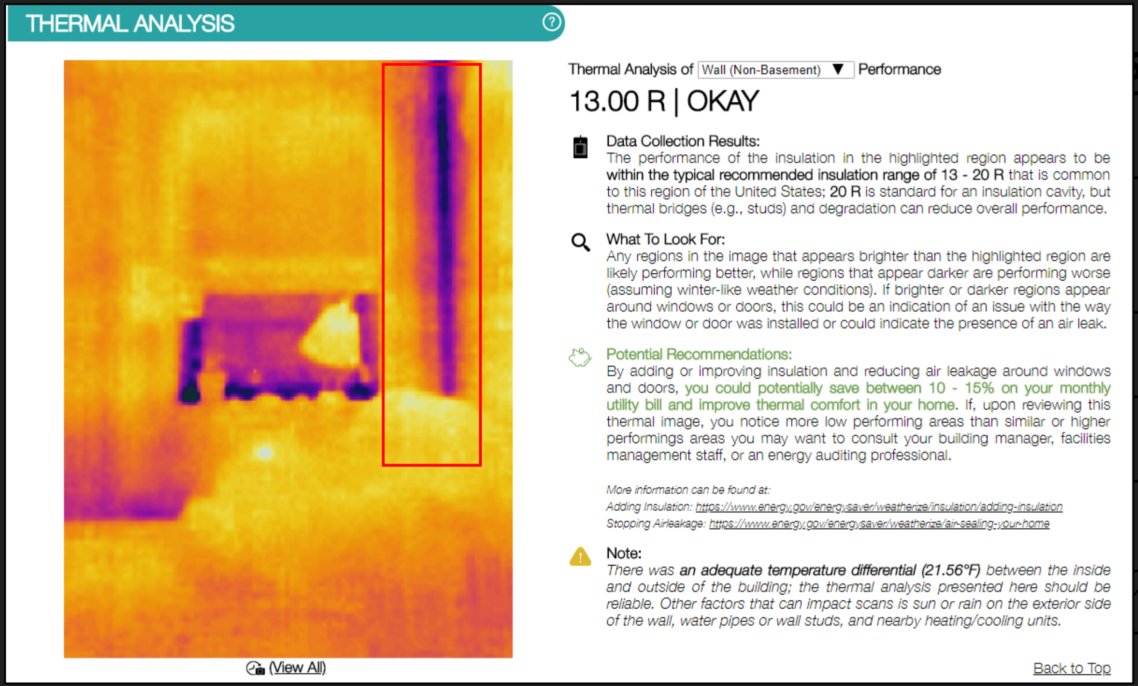

"It kind of gave me a why. **It's real cold here and it is below code.** Here's some further information you can look at. That was super helpful, **I can decide if I agree that this is a problem,** and it's telling me something I can do." –NI2

...sue	Issue was Found
	No
	Yes
	Less severe than anticipated
	Yes
	Yes
	No
...al camera mission	

Novice Study Findings: Sensor System Findings

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"The R-value is lower than I would've thought, especially in the living room which was upgraded approximately 10 years ago." –NI4

Novice Study Findings: Sensor System Findings

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"My reports were negative, I am not sure what else to glean from them." –NS5

NOVICE STUDY FINDINGS: SEMI-STRUCTURED INTERVIEW FINDINGS

Interactive Reporting

Data Privacy

Personal Confidence

Post-Mission Attitudes

Novice Study Findings: Semi-Structured Interview Findings

Interactive Reporting

Data Privacy

Personal Confidence

Post-Mission Attitudes

Interactive Reporting

Participants described the interactive report in several ways:

- 4 of 5 were positive about receiving the easy-to-read, automatically generated report.

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- 4 of 5 liked having longitudinal data and the additional depth the report provided by comparison to thermograms alone.

"I like the idea of having a report that I can refer to again afterward. You get that with pictures too, obviously. But the reporting aspect gives you more detail, [...] the fact that you had the environmental and air quality readings also gave you something more to look at." –NI3

Interactive Reporting

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- 4 of 5 liked having longitudinal data and the additional depth the report provided by comparison to thermograms alone.
- 3 of 5 envisioned using this data as a tool to communicate with professionals

"If there's a big problem, that's the thing I want to fix, but I don't trust that some guy is coming in and not trying to sell me." –NI2

NOVICE STUDY FINDINGS: SEMI-STRUCTURED INTERVIEW FINDINGS

Interactive Reporting

Data Privacy

Personal Confidence

Post-Mission Attitudes

Data Privacy

Participants were largely homogenous when it came to the privacy of their data:

- 4 of 5 desired explicit control over all data collected about/in their home.

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"If it were not an internet connected thing, if it were just a local network thing that I use in my house, that would be fine. If information is going out, then I have a big problem with technology like that." –NI2

Data Privacy

Participants were largely homogenous when it came to the privacy of their data:

- 4 of 5 desired explicit control over all data collected about/in their home.
- 1 of 5 desired aggregated data about their neighbor and explicitly advocated that local policy makers should have access.

Novice Study Findings: Follow-up Findings

Follow-up Findings

Participants were largely homogenous when it came to the privacy of their data:

- 5 of 5 reported thinking more about energy efficiency issues in their home since participation had ended.

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"It has made me generally more aware of where there might be issues and why." –NS3

Follow-up Findings

Participants were largely homogenous when it came to the privacy of their data:

- 5 of 5 reported thinking more about energy efficiency issues in their home since participation had ended.
- 2 of 5 reported making some repairs for air leakage issues; however, all reported that insulation issues required more savings and planning.

Follow-up Findings

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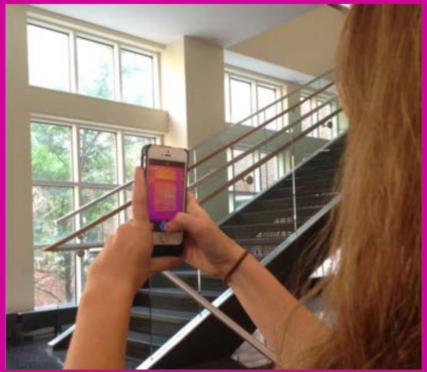
- 5 of 5 reported thinking more about energy efficiency issues in their home since participation had ended.
- 2 of 5 reported making some repairs for air leakage issues; however, all reported that insulation issues required more savings and planning.

"I'd say it's kind of too late once you get [the data] for the homeowner, unless you're about to do a renovation." –NI3

STUDY METHOD: NOVICE AND PROFESSIONAL STUDIES

Novice Study



Field Activities

Semi-Structured Interviews

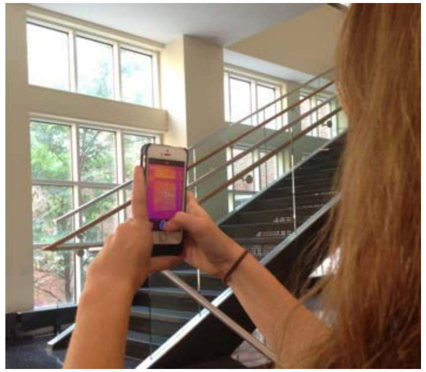
Professional Study

Part 1:
Semi-Structured Interviews

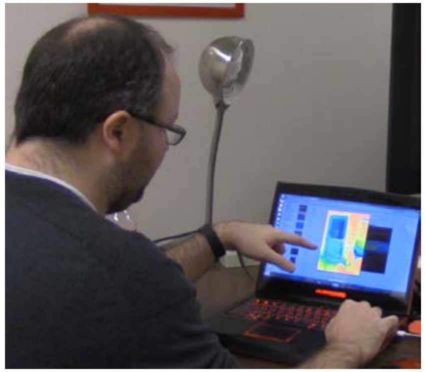
Part 2:
Presentation of Design Probes

Study Method: Novice and Professional Studies

Novice Study



Field Activities



Semi-Structured Interviews

Professional Study

Part 1:
Semi-Structured Interviews

Part 2:
Presentation of Design Probes

STUDY METHOD: PARTICIPANTS

5 Participants (All male)

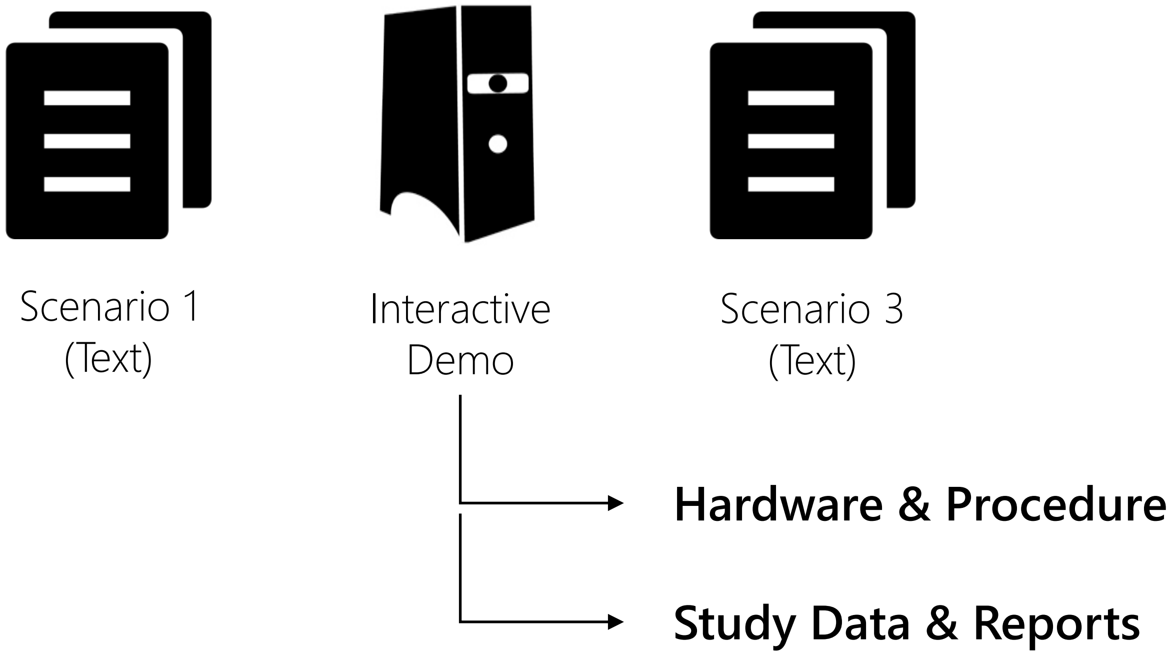
PROFESSIONAL STUDY METHOD: UPDATED PRESENTATION OF DESIGN PROBES

Scenario 1
(Text)

Interactive
Demo

Scenario 3
(Text)

Professional Study Method: Updated Presentation of Design Probes



PROFESSIONAL STUDY FINDINGS: PRESENTATION OF DESIGN PROBES

Raising Awareness

Providing Reliable Data

Relationship Building

Coverage and Installation

Motivating Action

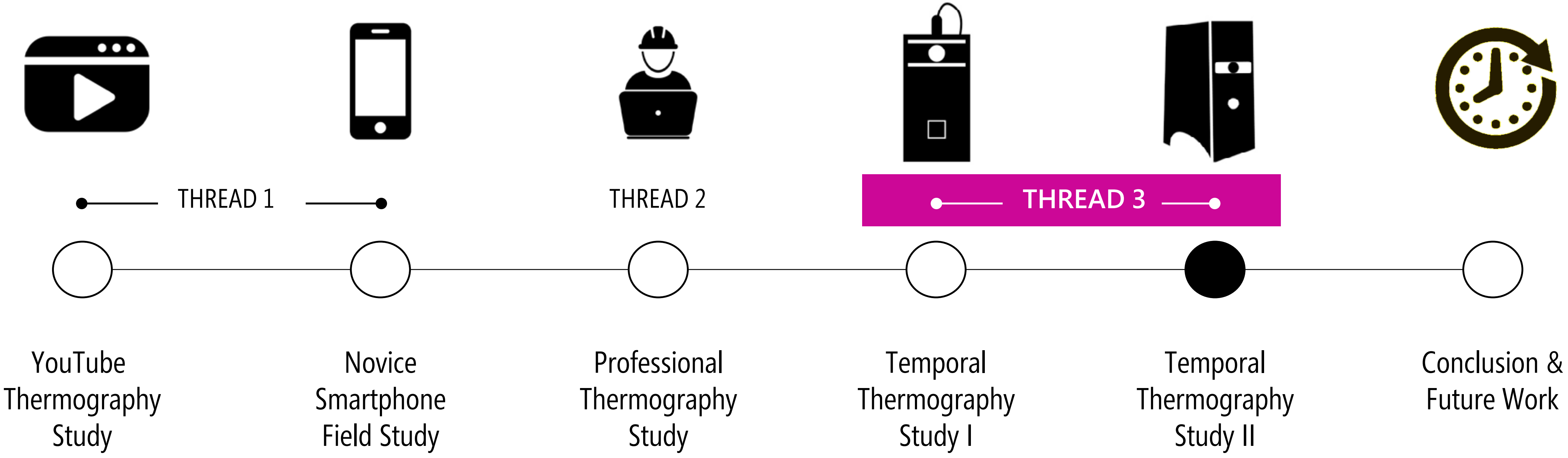
THREAD TAKEAWAYS: TEMPORAL THERMOGRAPHY STUDIES

- Temporal/Quantitative analysis provides more specific insights in the case of insulation performance.

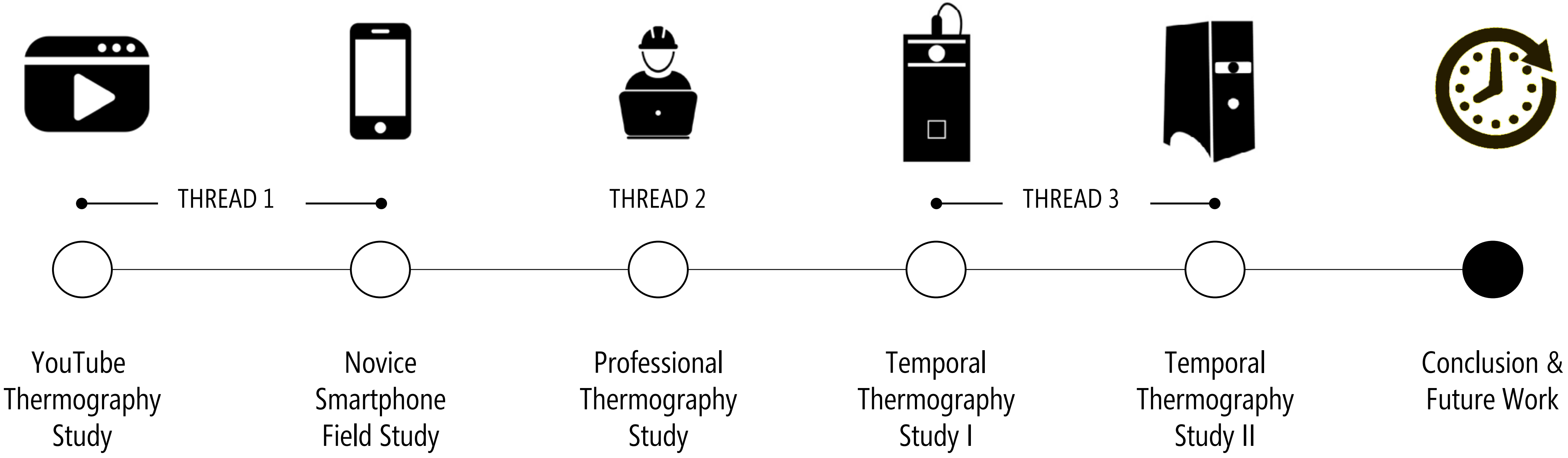
- Increasing homeowner agency opens new opportunities for professional auditor and homeowner relations.

- While we saw DIY solutions enacted, motivating larger-scale structural changes remains challenging.

Dissertation Overview



DISSERTATION OVERVIEW



DISSERTATION SUMMARY: OVERVIEW

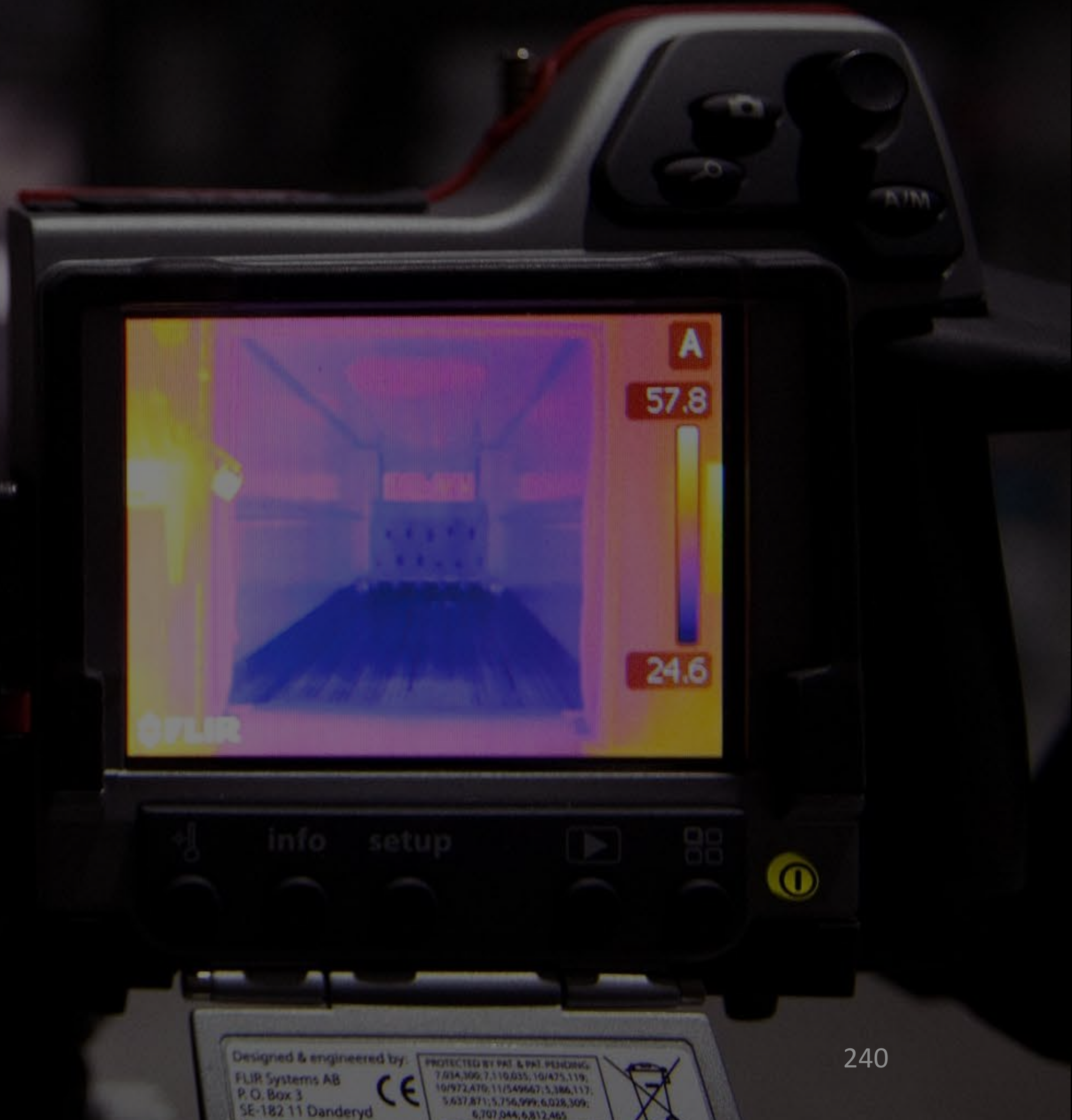
THREAD 1: Novice Studies		THREAD 2: Professional Studies	THREAD 3: Temporal Thermography Studies	
YouTube Thermography	Smartphone Thermography	Professional Thermography	Temporal Thermography I	Temporal Thermography II
Video Coding	Four-Week Field Study	Semi-Structured Interviews	Single Deployment with Professional	One-Week Field Study + Debrief Interviews with Novices
International Survey	Debrief Interview	Presentation of Design Probes	Usability Study with Novices	Semi-Structured Interviews + Presentation of Design Probes with Professionals
MobileHCI 2018	CHI 2017	CHI 2015	Ubicomp 2017	*

DISSERTATION SUMMARY: CONTRIBUTIONS

- Characterized novice and professional end-users of thermography

- Conducted human-centered explorations into the role of automation and the potential for pervasive thermographic scanning.

- Presented a novel, interactive temporal thermography system.

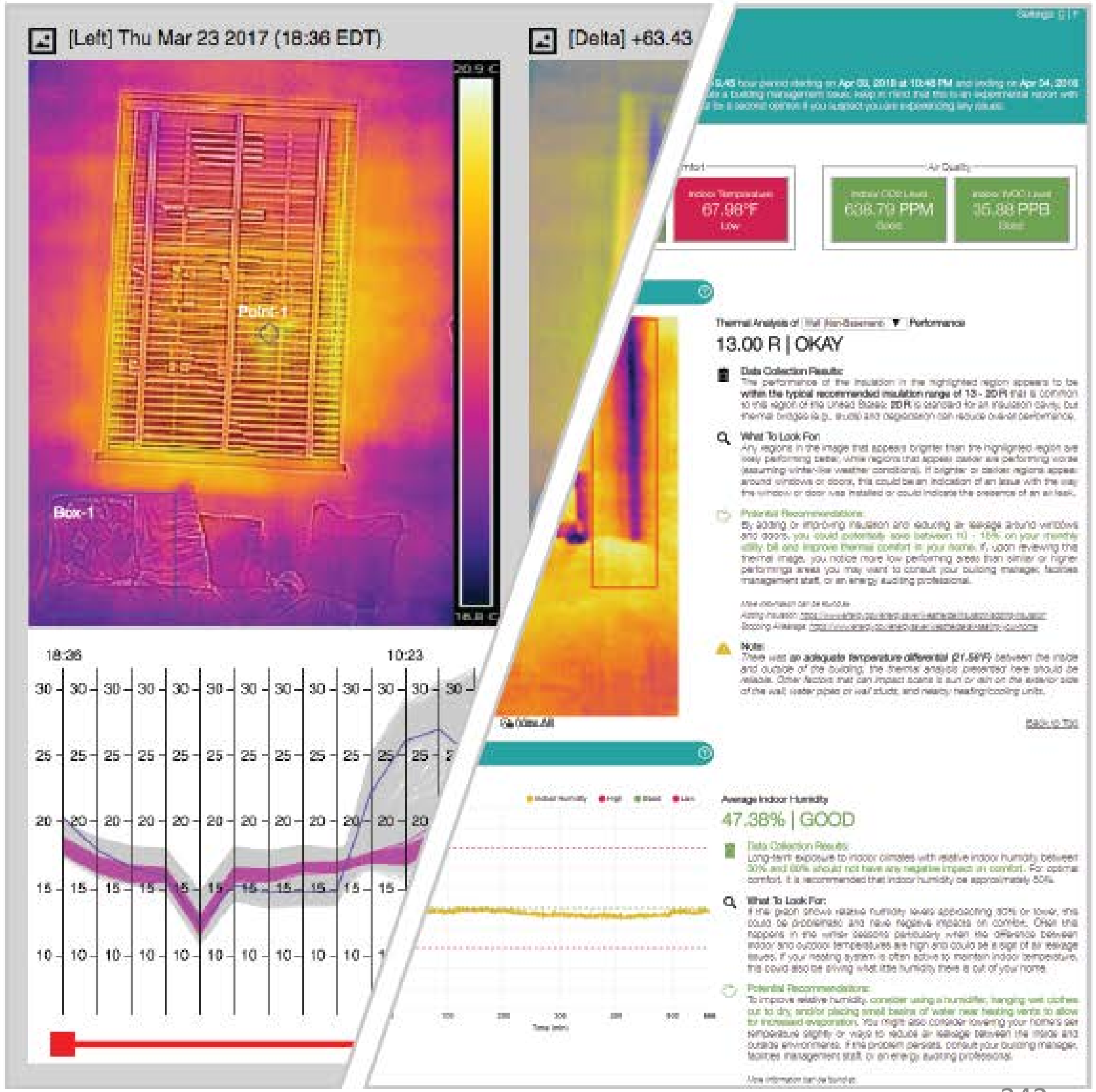


DISSERTATION SUMMARY: CONTRIBUTIONS

Contributions of this dissertation include:

- Characterization of novice and professional the end-users of thermography.
- **Design recommendations for future thermographic system to support their use.**
- A critical examination of recently proposed automated thermographic solutions.
- **Design recommendations for automated thermographic solutions.**
- A novel, building thermography system that support residential use.
- **A summary of key benefits of temporal thermography.**
- **Design recommendations for future, in-home temporal thermography systems.**

Dissertation Summary: Future Work



Dissertation Summary: Future Work

Framing and delivering energy efficiency recommendations is also an active area of research.

(Sussman *et al.* July 7th 2018)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Message framing for home energy efficiency upgrades

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ABSTRACT

Home energy efficiency upgrades reduce household energy consumption and provide financial and non-financial benefits to homeowners. This study is the first to experimentally test theory-driven message framing strategies to encourage homeowners to purchase recommended upgrades. A nationally representative sample of U.S. homeowners participated in six online experimental tests of message framing strategies. Successful framing involved changing how upgrade options were presented to subtly influence homeowners frames of reference. Respondents were more likely to report being willing to upgrade their homes after reading messages that espoused specific benefits of upgrading (bill savings, health and comfort), and after reading messages that took advantage of an anchoring heuristic (i.e., reducing the initial cost by the amount homeowners would spend on repairs anyway). Homeowners also chose to invest in more expensive upgrades if these were not listed next to extremely cheap "no-brainer" items with high annual savings. Homeowners in the 30–34 year age range, and those with children at home were most willing to upgrade.

1. Introduction

Home energy efficiency upgrades reduce household energy consumption and, therefore, reduce homeowners' energy bills. They also have numerous non-financial benefits, such as mitigating health conditions, [6], increasing a home's comfort [30], and reducing air pollution and greenhouse gas emissions associated with energy generation [27].

For many homeowners, the first step toward acquiring home energy efficiency upgrades is requesting a home energy assessment. During the assessment, a contractor or energy efficiency expert visits the home, performs diagnostic tests, and discusses the residents' concerns about their home's performance. The contractor then prepares a report listing the recommended home upgrades and discusses the report with the homeowners to help them decide which upgrades, if any, should be installed.

Assessors' conversion rates, the rate at which customers purchase recommended upgrades, can sometimes be a problem for home energy assessment programs (e.g., [9,23]). Frequently, participants go through the process of getting an assessment but do not purchase the recommended upgrades, or only purchase the cheapest upgrades with the shortest payback periods (e.g., [32]). One German study found that commercial building owners became more knowledgeable after energy assessments, but were not significantly more likely to invest in upgrades [35]. In a survey of nearly 500 assessors, 71% estimated that homeowners purchase at least one recommended upgrade "fairly often" or "always," but only 1% of homeowners follow all of the recommendations [31].

Many factors influence homeowners' decisions to invest in home energy upgrades. Some of these are beyond the control of the assessor, such as the homeowners' financial situation, the price of energy, and the so-called "split incentive" situation in which the home renter (as opposed to the owner) reaps the benefits of the homeowner's investment [7]. Other external drivers include the pre-existing need for household repairs, and the presence of a household member who is comfortable installing upgrades [40]. However, the home energy assessor also has control over some of the factors that determine homeowner investment in energy upgrades, such as interpersonal interactions, performing certain diagnostic tests, and providing personally tailored reports [2,21].

The aspect of the assessment examined in this study is the framing of the home energy upgrade message...

* Corresponding author.
E-mail address: reuven.sussman@...

DISSERTATION SUMMARY: FUTURE WORK

Multi-Sensor Deployments


Designation: C 177 – 04

Standard Test Method for
Steady-State Heat Flux Measurements and Thermal Transmission Properties by Means of the Guarded-Hot-Plate Apparatus[1]

1. Scope

INTERNATIONAL STANDARD

ISO 9869-1

First edition 2014-08-01

...ermal insulation — Building ...ents — In-situ measurement ...hermal resistance and thermal ...smittance —

...flow meter method

Standard for Temporal Thermography

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