The potential and challenges of inferring thermal comfort at home using commodity sensors

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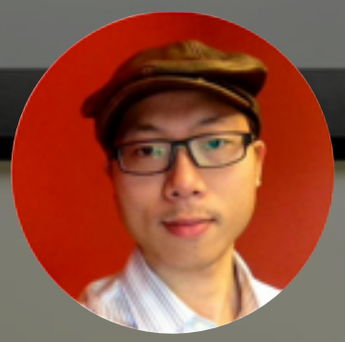


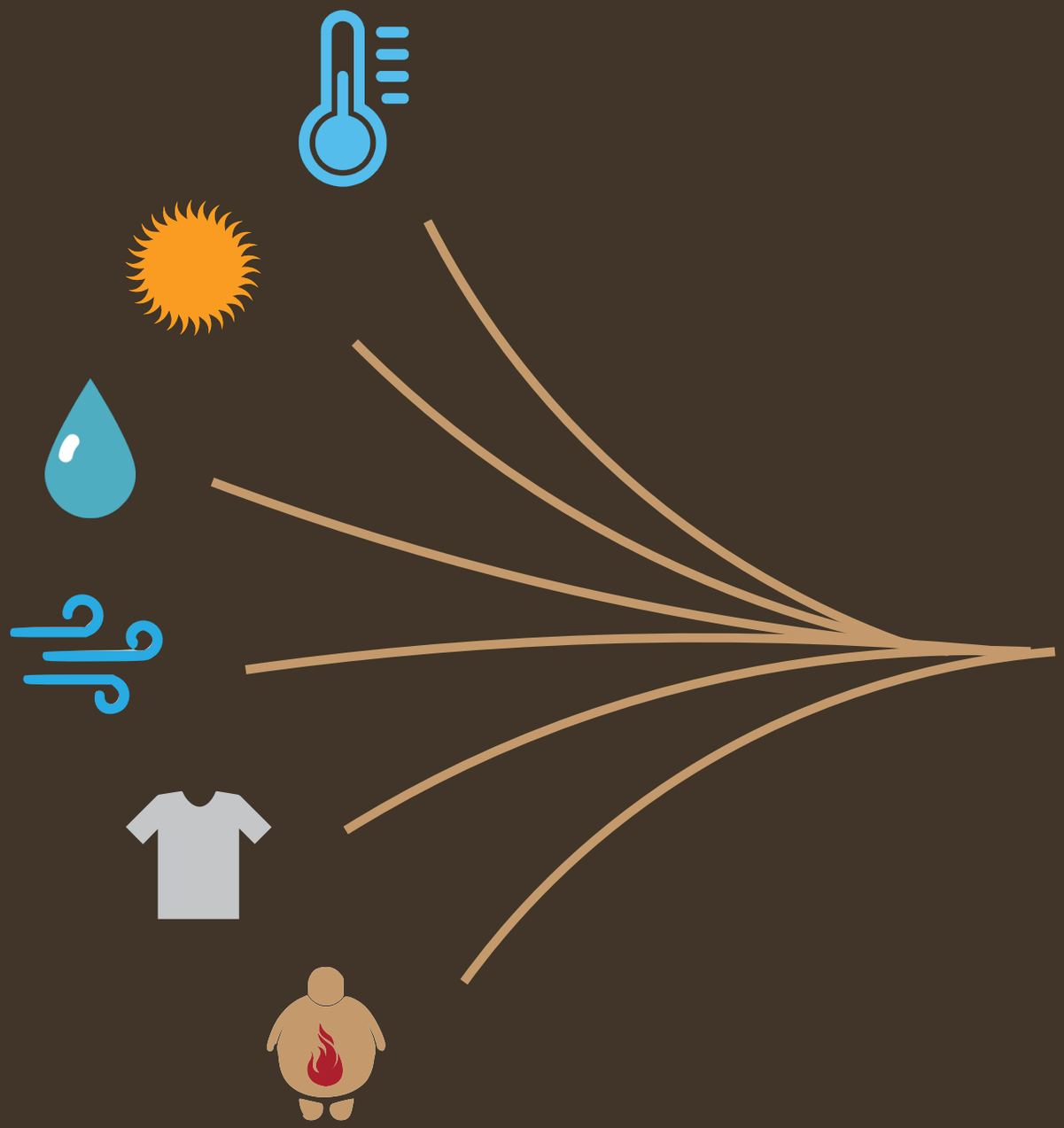
Understand the connection between psychological and physiological factors

Create UbiComp applications to reduce energy consumption and increase comfort

[Clear et al., 2013; Clear et al., 2014, Feldmeier & Paradiso, 2010]

Predicted Mean Vote (PMV)

[Fanger, 1970]



PMV Index

+3 (warm)

-3 (cold)

Why Now

Not suitable for inferring thermal comfort at home, in naturalistic settings (in-situ), and for UbiComp applications

Require cumbersome sensors, extensive questionnaires or human observers

[e.g., Baker & Standeven, 1996; Beizaee & Firth, 2011]

Models are designed for large groups of people (e.g., offices), not small groups of people, such as home

[Jones, 2002]

Home is one of the places people exhibit adaptive behaviors the most (e.g., open windows, drink cold beverage)

[Nicol & Humphreys, 2002]

Our Approach

- ✦ Skin Temperature
- ✦ Galvanic Skin Response
  (Approximate sweat level)
- ✦ Activity Level
  (Approximate metabolic rate)

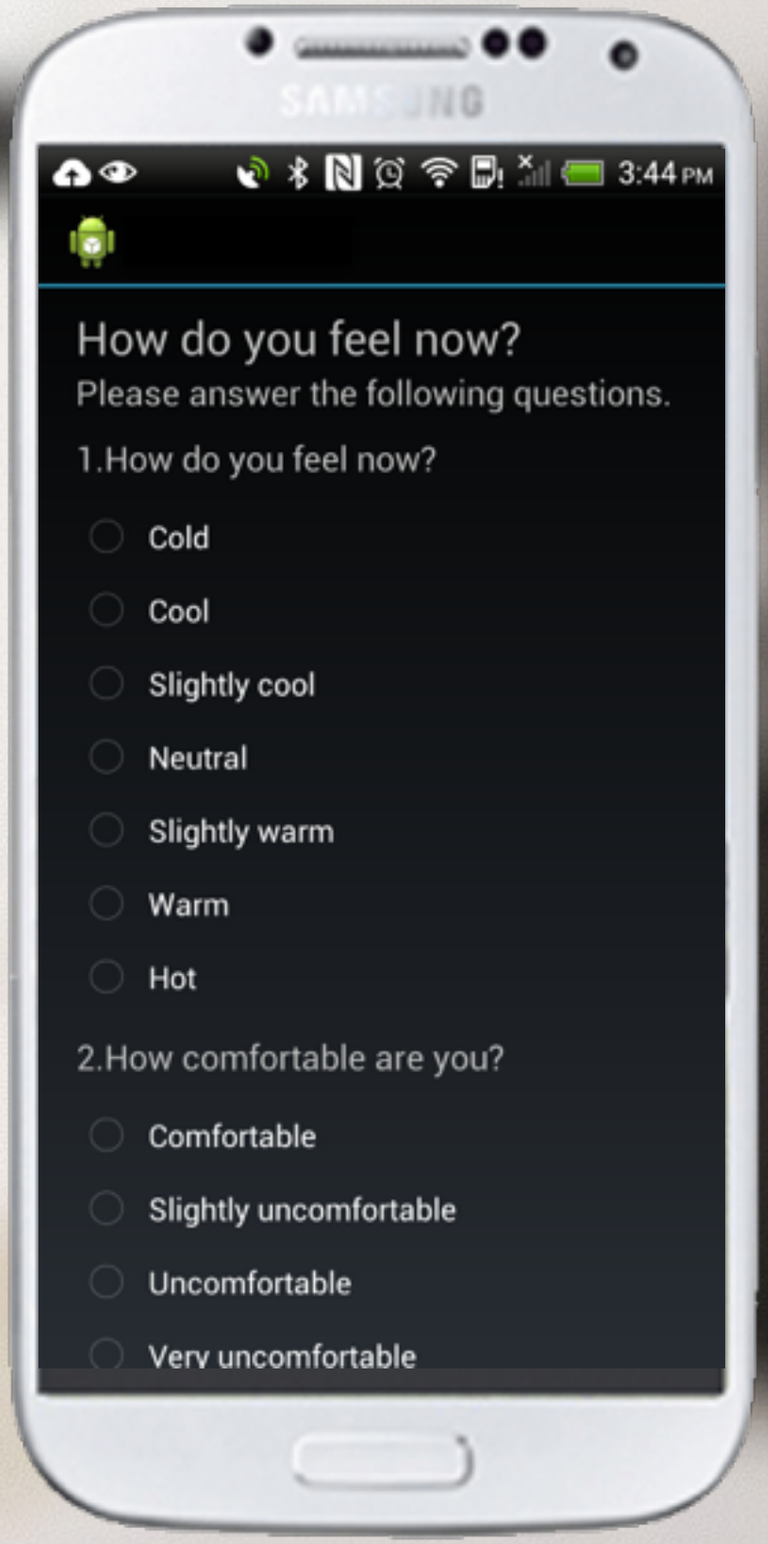
- Near-body Air Temperature

- Room Temperature
- Humidity

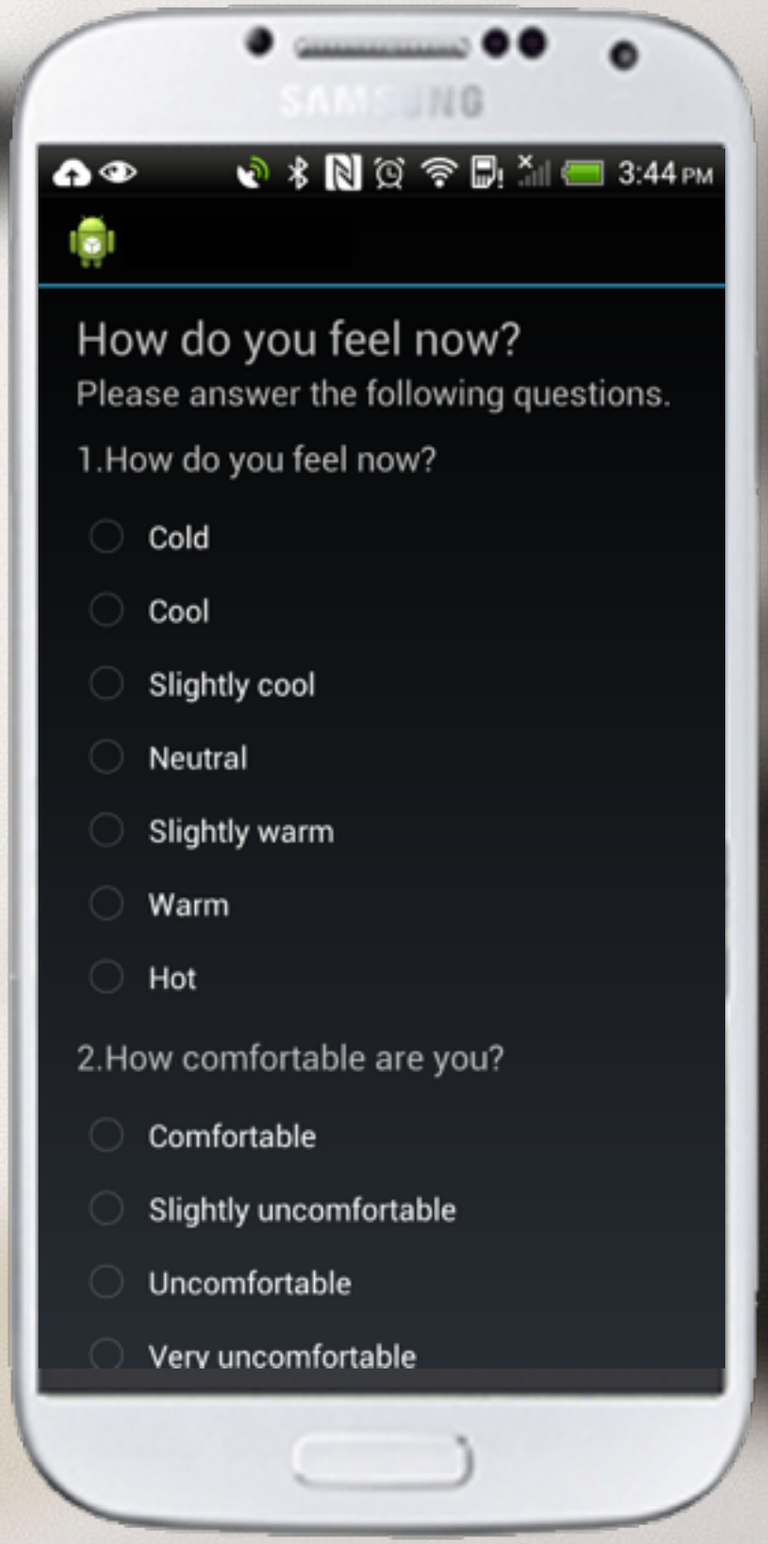
You feel cold!

Warm, cold,
or comfortable?

Warm


3:44 PM
How do you feel now?
Please answer the following questions.
1.How do you feel now?
Cold
Cool
Slightly cool
Neutral
Slightly warm
Warm
Hot
2.How comfortable are you?
Comfortable
Slightly uncomfortable
Uncomfortable
Very uncomfortable

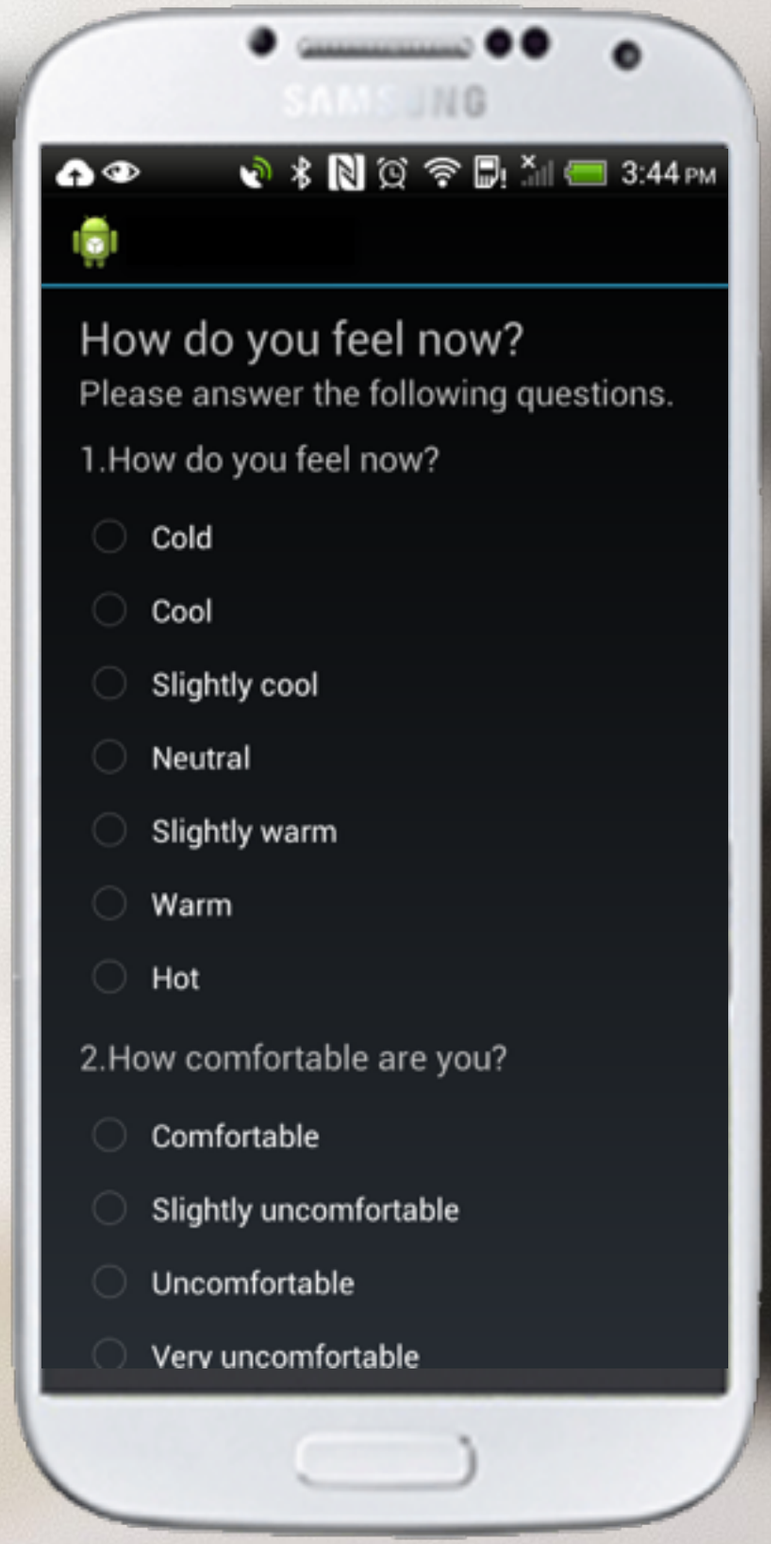

SAUNA JOURNAL
Thu Sep 04
Today
Sat Sep 06
Thermal Comfort Journal
2014-09-05
You felt cold and slightly uncomfortable at 7:09 AM
Memo
Activity: eating
Clothing level: light
Location: Dining room
Just got up
Q1: What were you doing at 7:09 AM?
Eating
Location
Dinning room
From
7:00 AM
To
7:30 AM
Type in additional activities
If you have any problem answering the above question, answer and explain here.
Next
Thermal Labels
SKIN TEMP @Wearable
STEPS @Wearable
MOTION @Bedroom
MOTION @Dinning room
MOTION @Living room
MOTION @Kitchen
HEART RATE @Wearable



Minuku Mobile ESM Tool

- **7-level Thermal Sensation**
  {Cold, …, Warm}
  [ASHRAE STANDARD 5-2005]

- **4-level Comfort Sensation**
  {Comfortable, … ,Very Uncomfortable}
  [Gagge et al., 1967]



- Current activity
- Clothing level
- Location at home
- Reasons of discomfort/comfort

Web-based Diary Tool

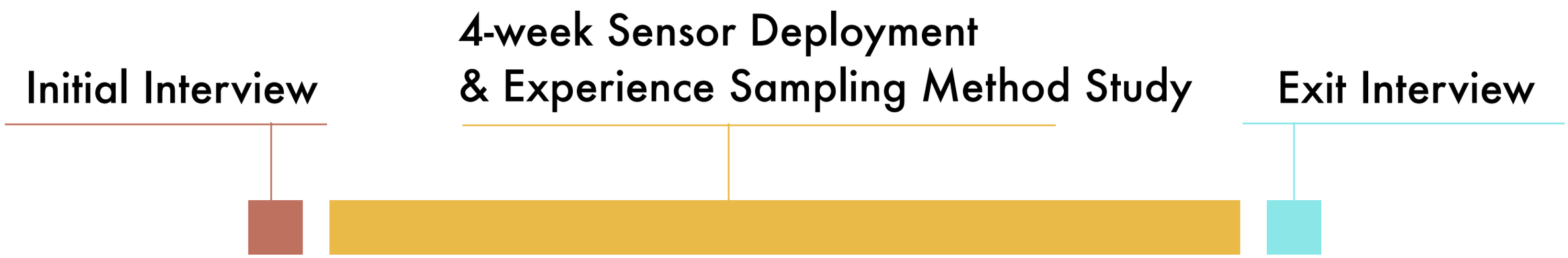
- Current & previous activity
- Start time and end time of activities
- Detail reasons

Key Questions

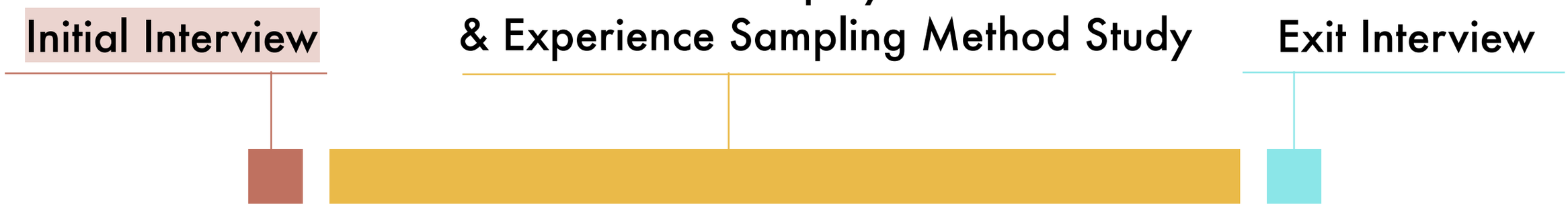
1. Feasible?

2. Challenging Situations?

Study Design



Study Design



- Habit of using heating and cooling system
- Daily routines

Study Design

Initial Interview

4-week Sensor Deployment
& Experience Sampling Method Study

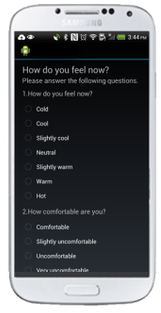
Exit Interview

1 Indoor sensors

2 Wearable sensors

3 Minuku

4 Diary tool



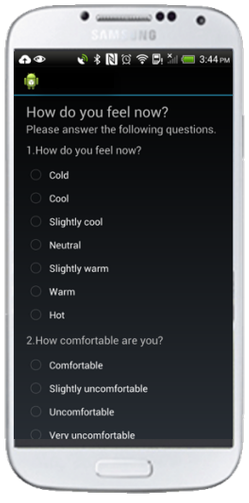
5 Home Hub

Study Design

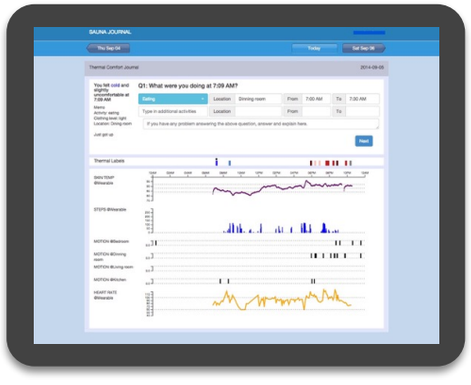
Initial Interview

4-week Sensor Deployment
& Experience Sampling Method Study

Exit Interview

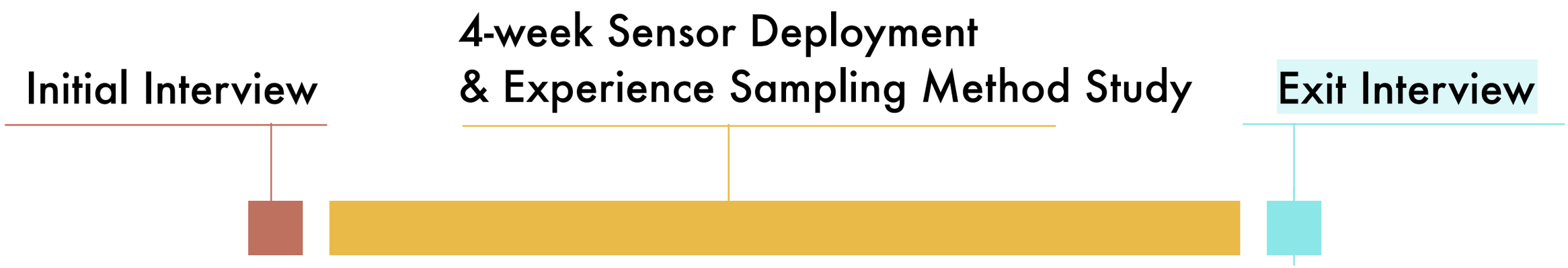


- Send a questionnaire **every 30 minutes** whenever the participant was **at home and awake**
- Participants were expected to answer **at least 6 reports** per day



- At the end of the day, log activities and **reasons of comfort/discomfort**

Study Design



- Study why people reported comfortable or uncomfortable if information were missing

Dataset

	Total
# participants	9
# households	7
# reports	1132

Key Questions & Two Analyses

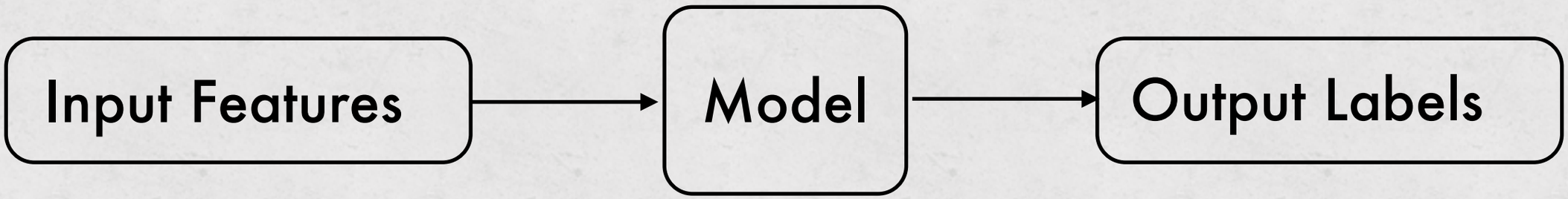
1. Feasibility

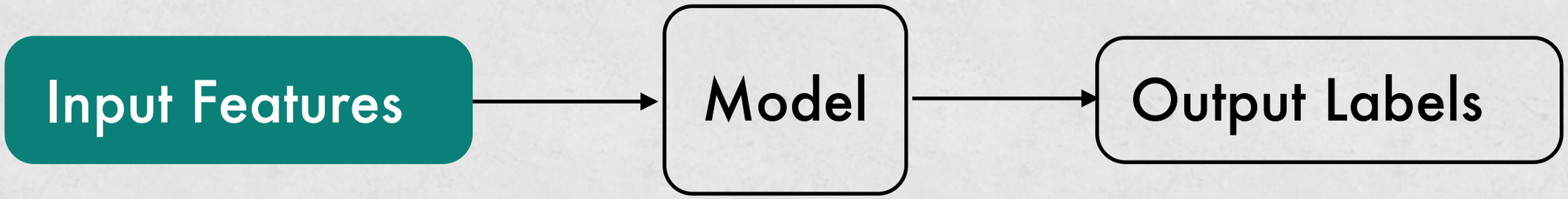
Analysis 1:
Accuracy of our approach

2. Challenging Situations

Analysis 2: Investigate the ESM & interview data

Analysis 1: Feasibility

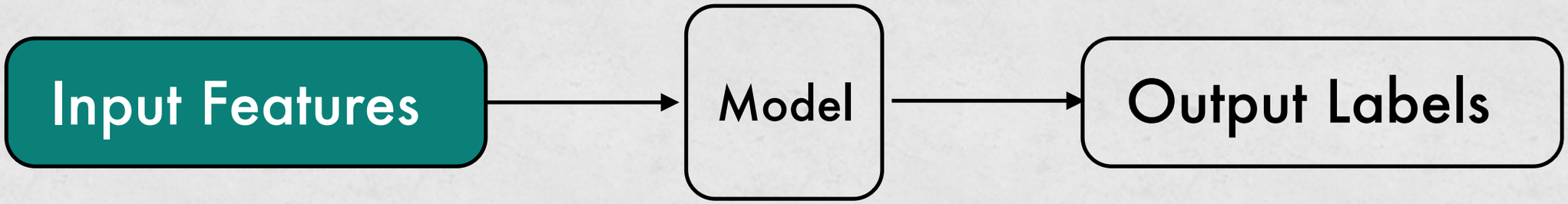




BASE

NO-CLO

Wearable



BASE

NO-CLO

Wearable

Self-report

- Clothing level

Room

- Air Temperature
- Humidity

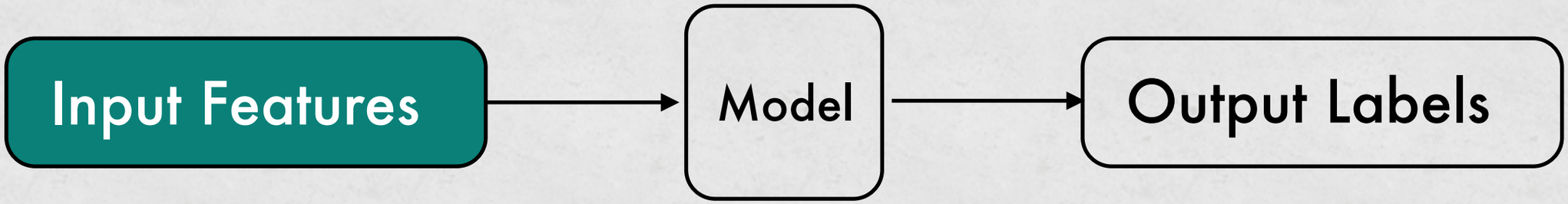
Inferred

- PMV index

Wearable

- Near Body Air Temperature
- Skin Temperature
- Galvanic Skin Response
- Activity Level

30, 10 mins, current



BASE

NO-CLO

Wearable

Is having **sensors** enough?

Self-report

- Clothing level

Room

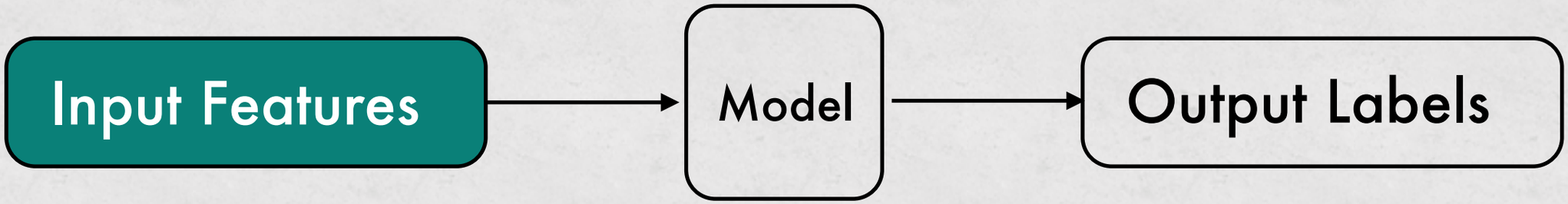
- Air Temperature
- Humidity

Inferred

- PMV index

Wearable

- Near Body Air Temperature
- Skin Temperature
- Galvanic Skin Response
- Activity Level



BASE

NO-CLO

Wearable

Is having **wearable** sensors enough?

Self-report

- Clothing level

Room

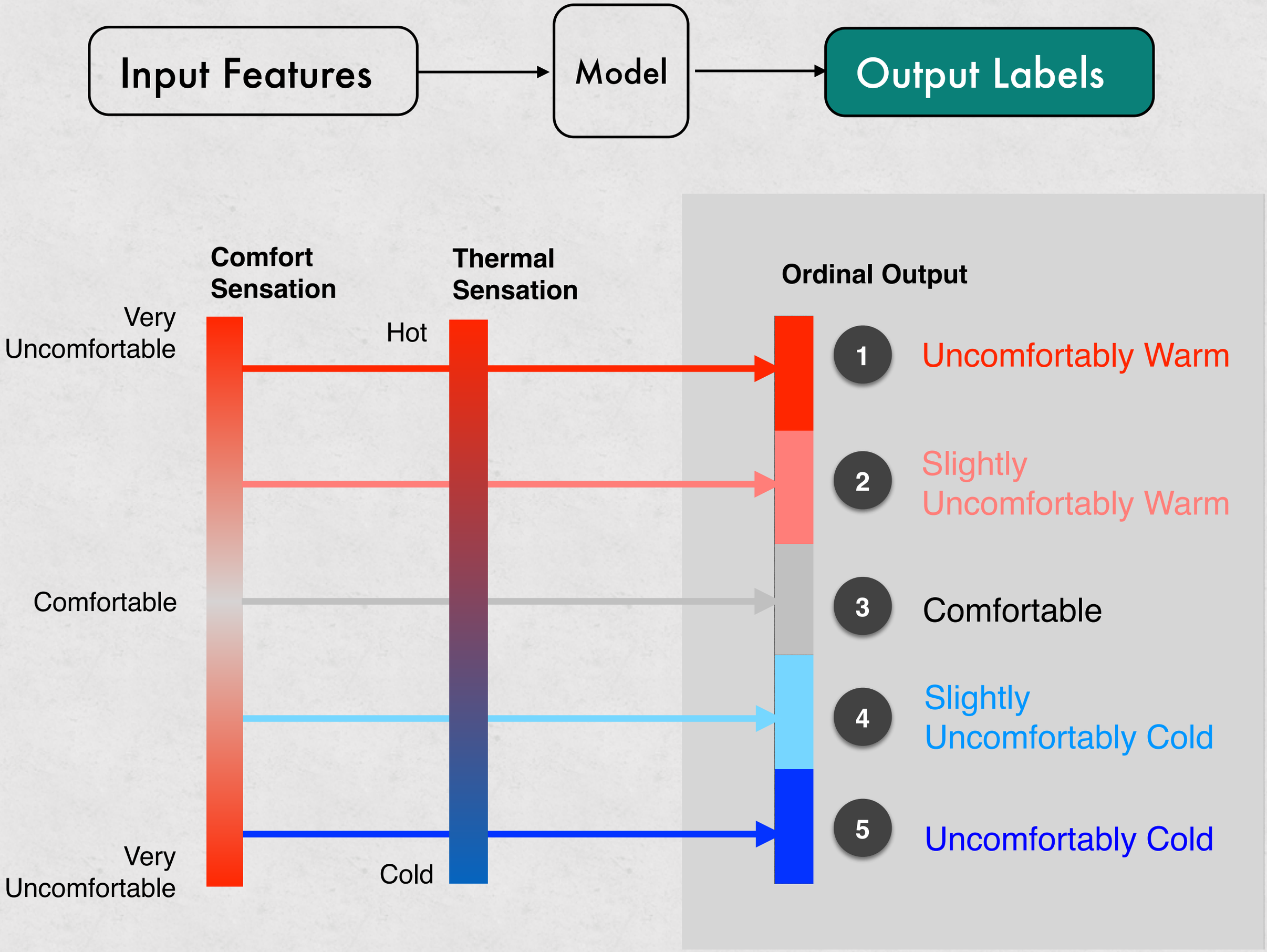
- Air Temperature
- Humidity

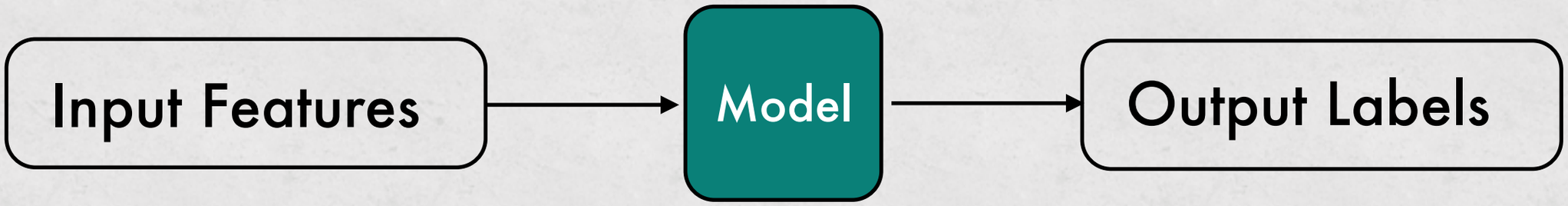
Inferred

- PMV index

Wearable

- Near Body Air Temperature
- Skin Temperature
- Galvanic Skin Response
- Activity Level


Input Features
Model
Output Labels
Comfort Sensation
Thermal Sensation
Ordinal Output
Very Uncomfortable
Hot
Comfortable
Cold
Very Uncomfortable
1
Uncomfortably Warm
2
Slightly Uncomfortably Warm
3
Comfortable
4
Slightly Uncomfortably Cold
5
Uncomfortably Cold



Machine Learning Model

- SVM + Ordinal Classifier
  [Fernández-Delgado et al., 2014]

Baseline Models

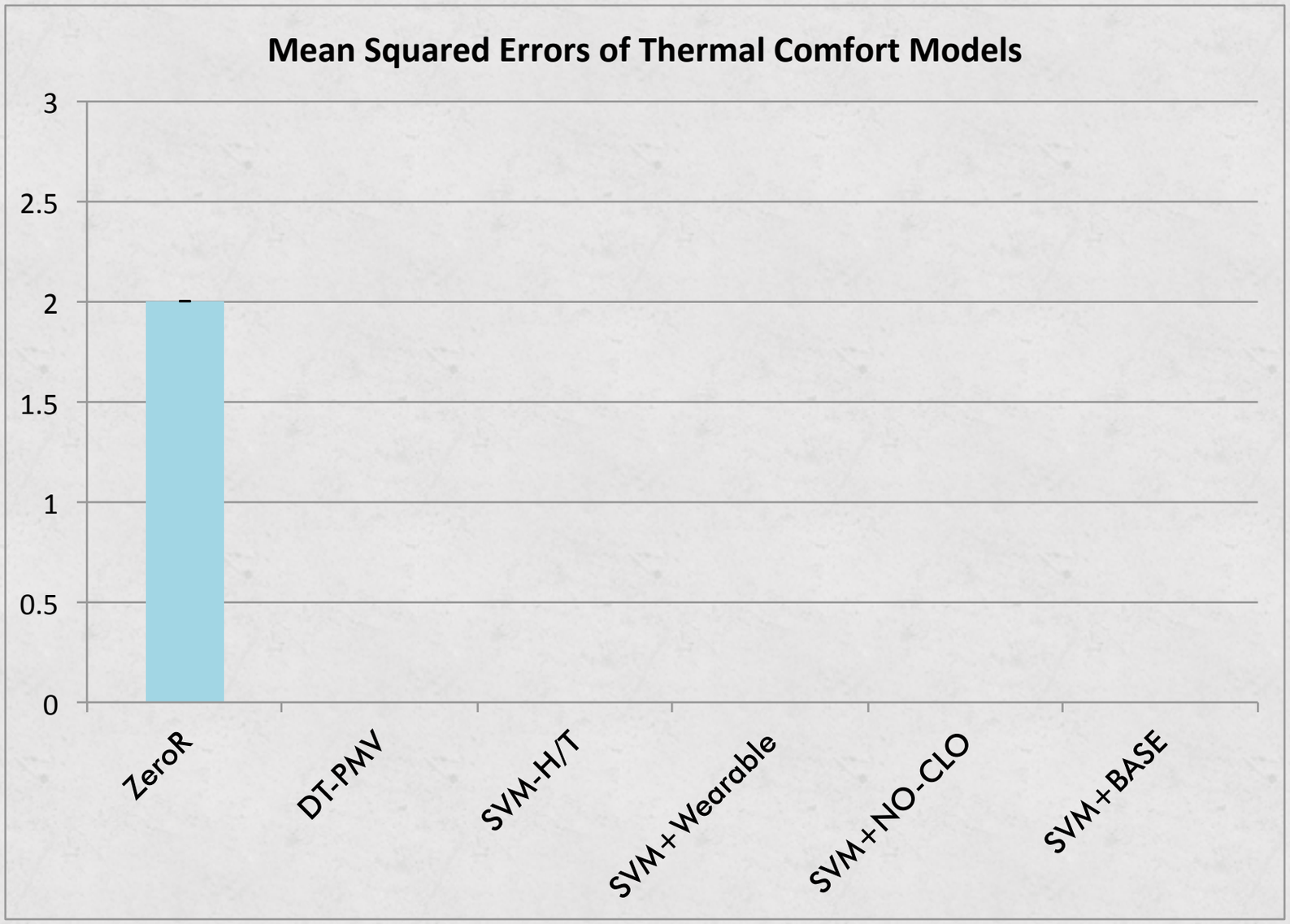
- ZeroR (always predict comfortable)
- Decision Tree with PMV
- SVM with Air Temp and Humidity

[Feldmeier & Paradiso, 2010]

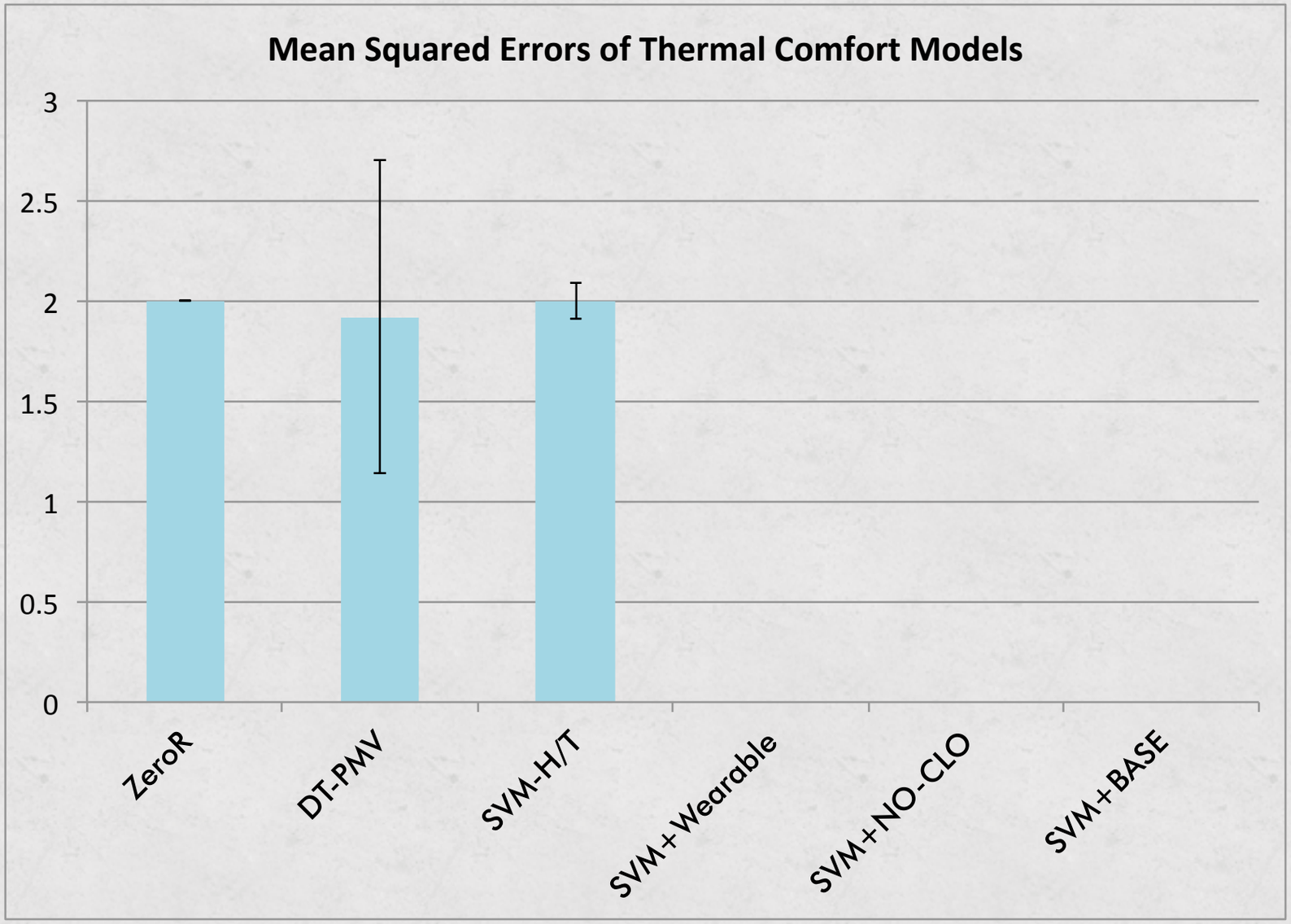
Evaluation Metric

- Mean Squared Error $$\mathrm{MSE} = \frac{1}{n}\sum_{i=1}^{n}(\hat{Y}_i - Y_i)^2$$

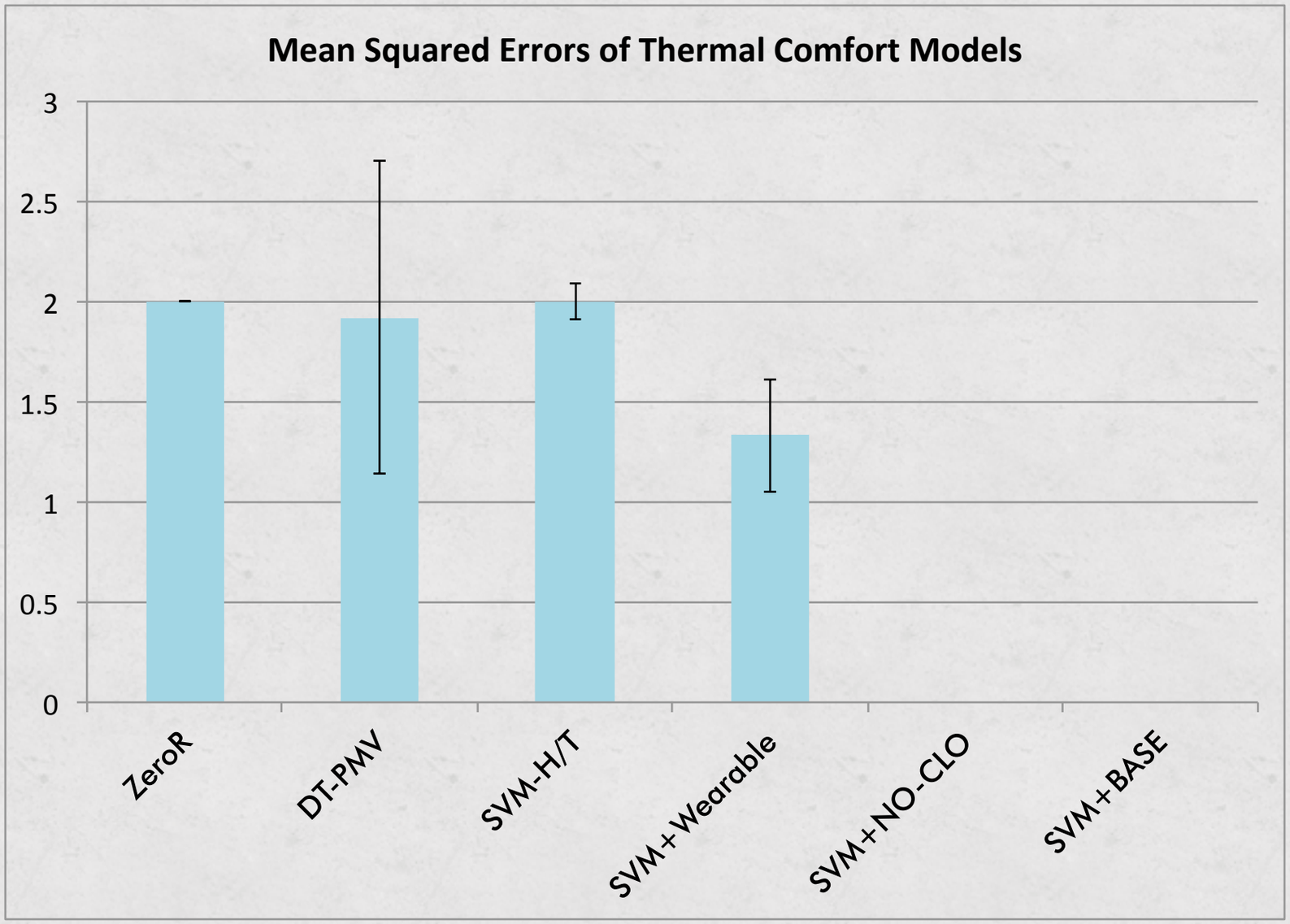
If we always infer comfortable (COM)



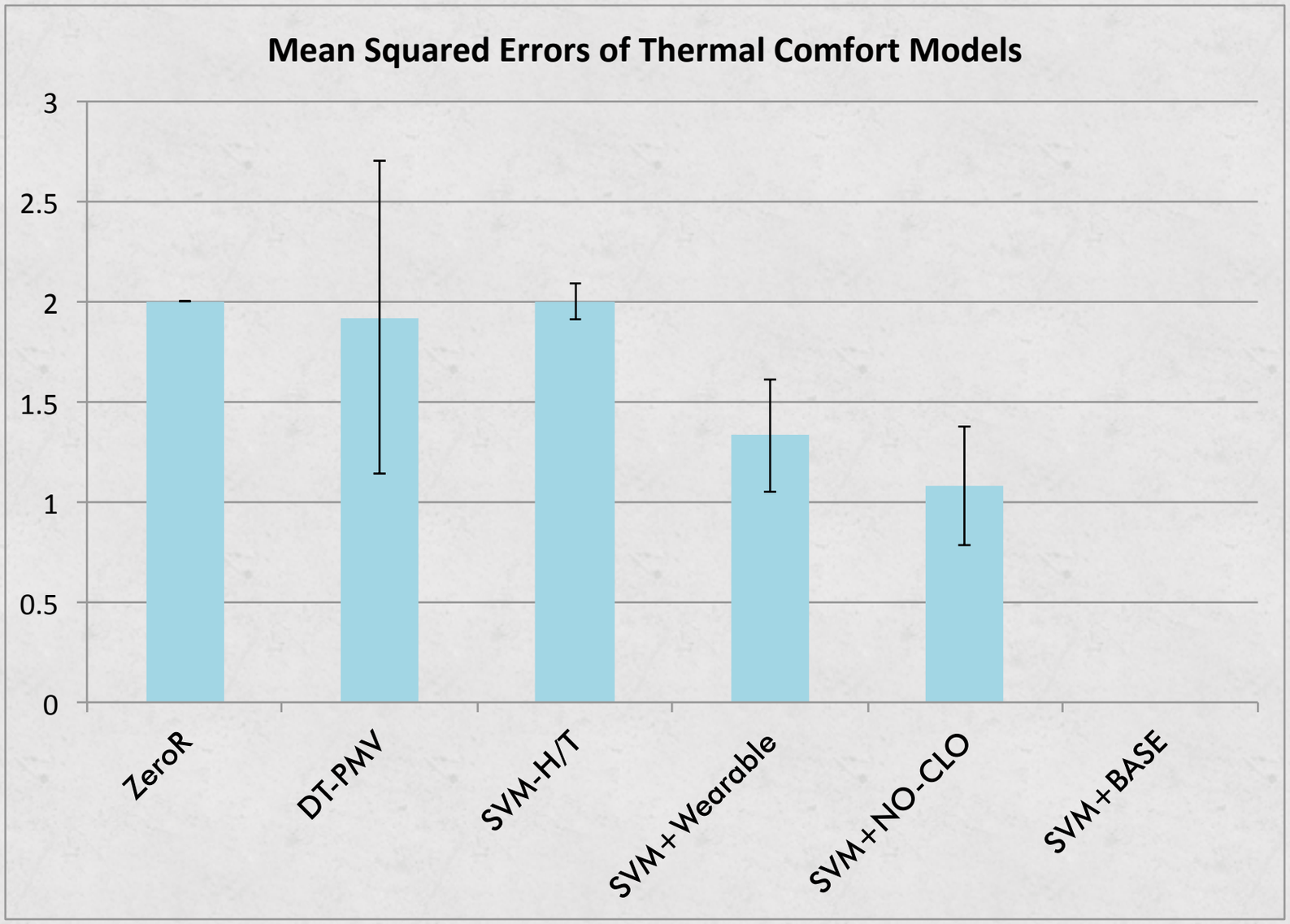
Previous approaches



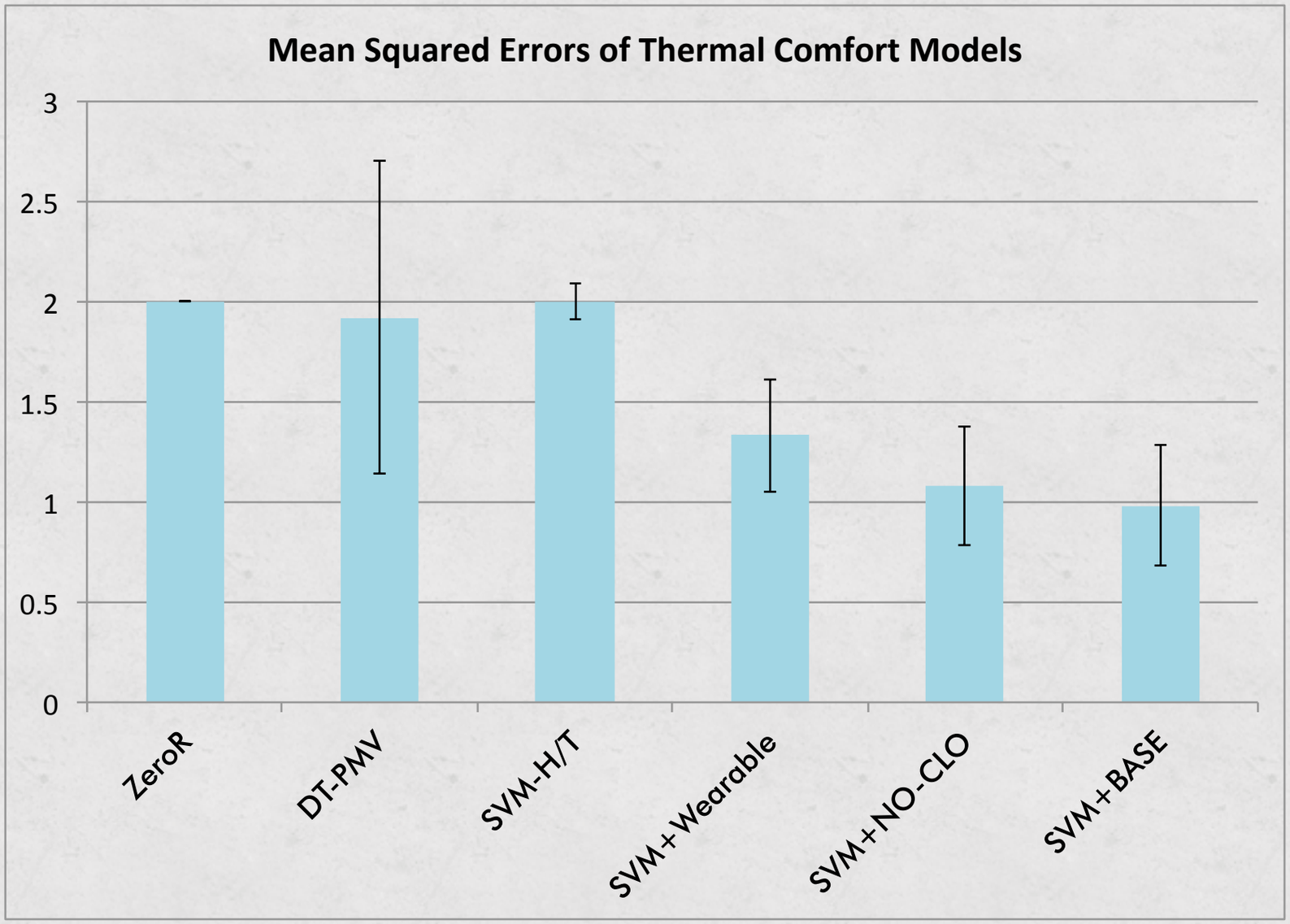
Use features from wearable sensors



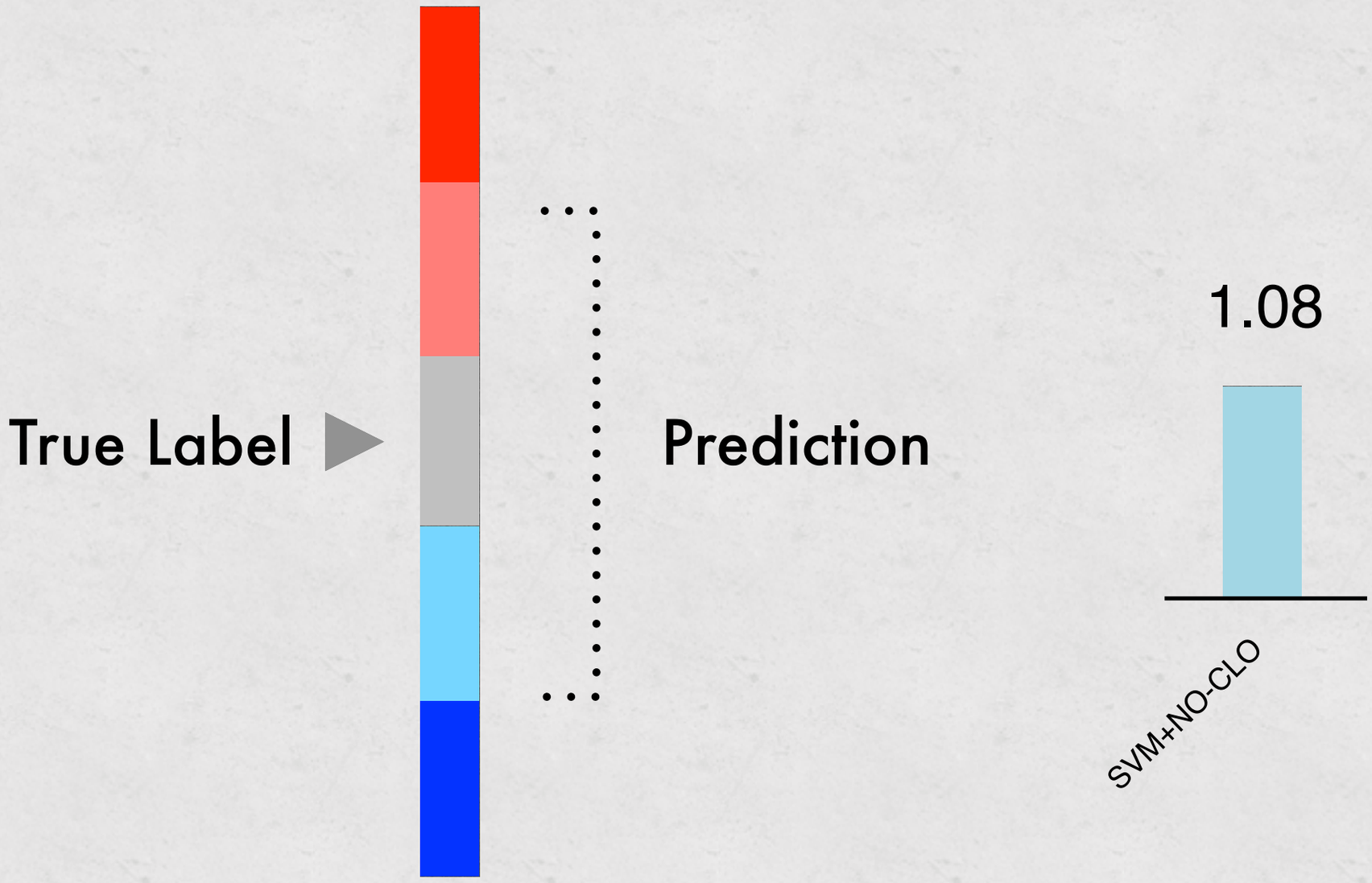
Add features from indoor sensors



Add clothing information



Using only sensor data



Three things we learn from analysis 1

- Previous techniques are not suitable for inferring comfort at home in naturalistic settings

- Using both wearable fitness trackers and indoor sensors, we are able to reduce the error by 50%

- Significant errors still remain even after using all these sensors

Analysis 2
Challenging Situations

Confusion Matrix

		PREDICTION				
		UC-Cold	**S-Cold**	**COM**	**S-Warm**	**UC-Warm**
TRUE	**UC-Cold**	8	17	0	0	0
	S-Cold	7	39	15	8	0
	COM	22	186	410	271	10
	S-Warm	3	8	17	64	7
	UC-Warm	2	1	2	26	9

Challenging Situations

1. Short-term effect or local heat source
2. Dynamic transitions
3. Extra cover or un-captured wind effect
4. Light weight exercise or housework
5. Problems with data collection and data handling
6. Individual difference

Challenging Situations

1. **Short-term effect or local heat source**
2. **Dynamic transitions**
3. **Extra cover or un-captured wind effect**
4. Light weight exercise or housework
5. Problems with data collection and data handling
6. **Individual difference**

Short-Term Effect or Local Heat Source

"I felt warmer because I was reading the news and checking email with my laptop on my lap. Even though the room was still cool from earlier, **the laptop made me feel warm and kept me comfortable**." - P3

Dynamic Transitions

P4 reported comfortable while the prediction is uncomfortably cold

Just woke up in the morning at the time and commented “The room was [at] a comfortable temperature”.

Room temperature: 18.9 °C
Skin temperature 15 minutes before: 31 °C (was in bed)

Extra Cover & Un-captured Wind Effect

- P11 reported "**The puppy was in my lap, which warmed me up**"
- "Was still in bed **under heavy blankets**"

Extra Cover & Un-captured Wind Effect

- P1 reported comfortable while the prediction is uncomfortably warm

She reported **having her fan on while her skin temperature was 33.7°C** and air temperature was 27.8°C

Individual Difference

- P10 reported comfortable, while the prediction showed uncomfortably cold

"At the desk, my hands were getting cold. **I am used to my hands getting cold** though so it wasn't uncomfortable."

Skin temperature 26.7 °C (80 °F)
Room temperature 16.5 °C (61.7 °F)

Possible Ways of Improvement

- **Improve the detection on local heat source and extra cover**
  - Part-of-room indoor positioning
  - The temperature difference between wearable and indoor sensors
- **Consider individual difference**
  - Personalized Models

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- **Improve the detection on local heat source and extra cover**
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Possible Ways of Improvement

- **Improve the detection on local heat source and extra cover**
  - Part-of-room indoor positioning
  - The temperature difference between wearable and indoor sensors

- **Consider individual difference**
  - ~~Personalized Models~~
  - Groupization approach
    - Community Similarity Network [Lane et al., 2014].

Conclusion

- Demonstrate the **feasibility of inferring people's thermal comfort** at home in-situ using off-the-shelf wearable and in-home sensors
- Deploy an experimental sensing system to 9 households along with **a ESM study to investigate the feasibility**
- **Identify 6 challenging situations** for inferring thermal comfort along with **possible solutions**

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Acknowledgment

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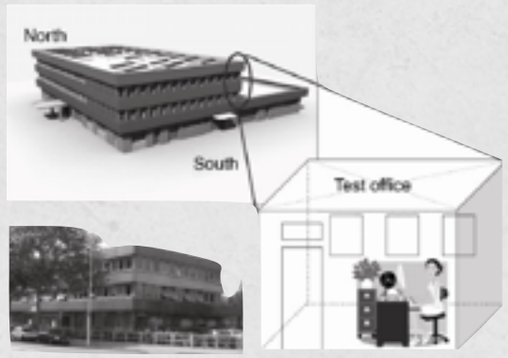
Members of Interaction Ecologies Group

Extra Slides

Design better buildings to increase quality of life

In-situ Comfort Sensing

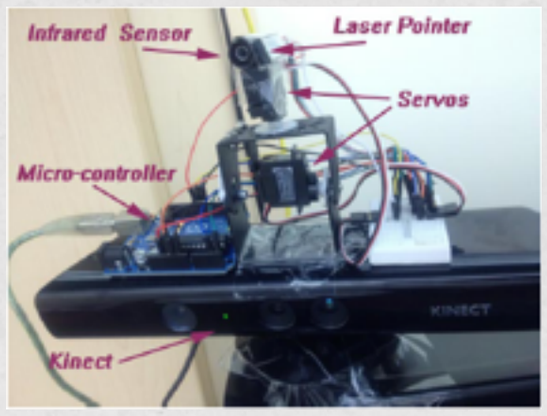


Indoor sensors (include wind speeds of desk fans)

[Nouvel & Alessi, 2012]

Use wearable & indoor sensors to infer people's comfort

[Feldmeier & Paradiso, 2010]



Use Kinect & IR sensors to infer activity and clothing levels

[SPOT: Gao & Keshav, 2013]

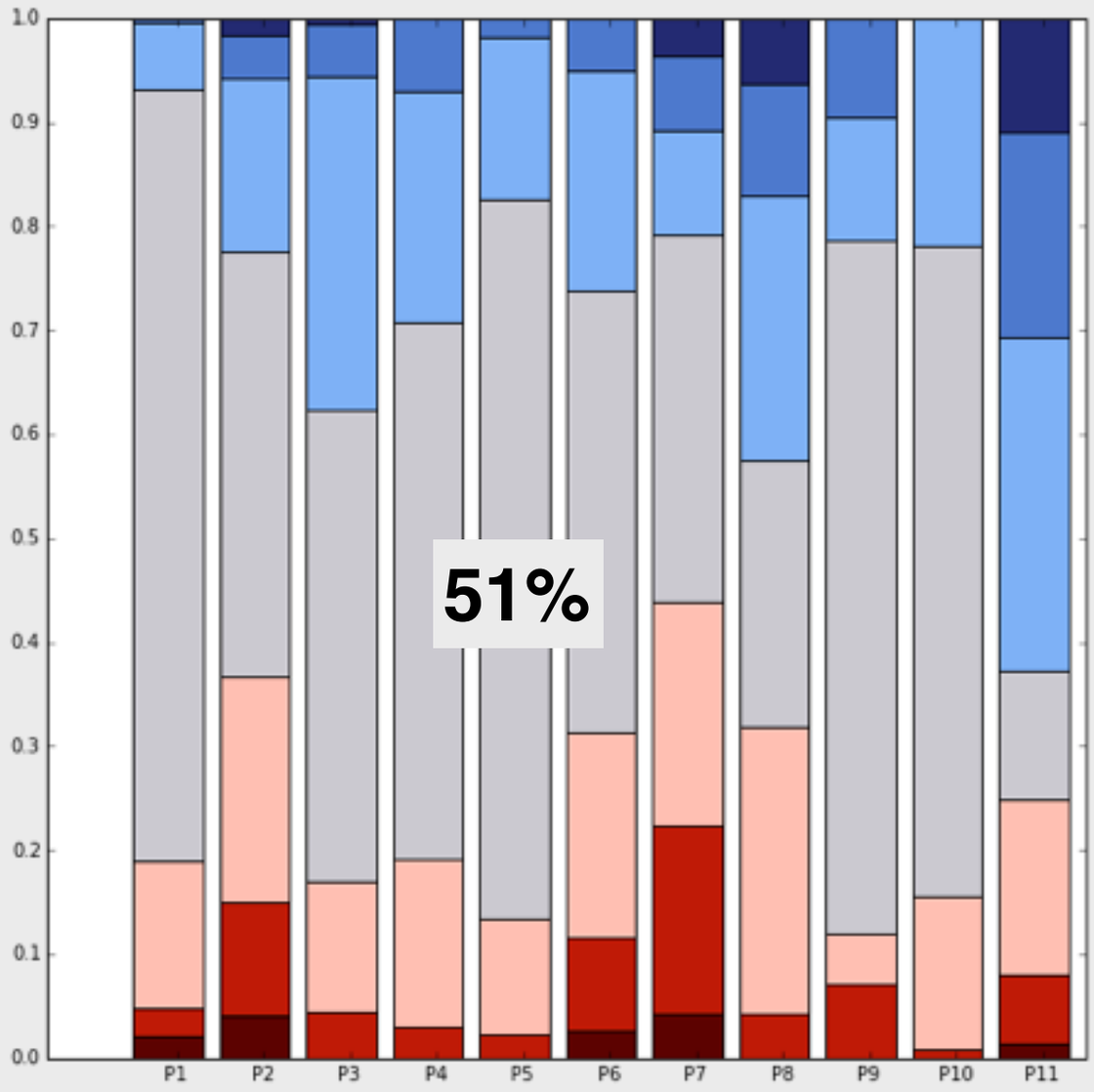
Intuition of This Index

- **Thermal sensation itself cannot represent the intensity of discomfort**
  Some people interpret “cold” or “slightly cool” as a preferred, comfortable temperature.

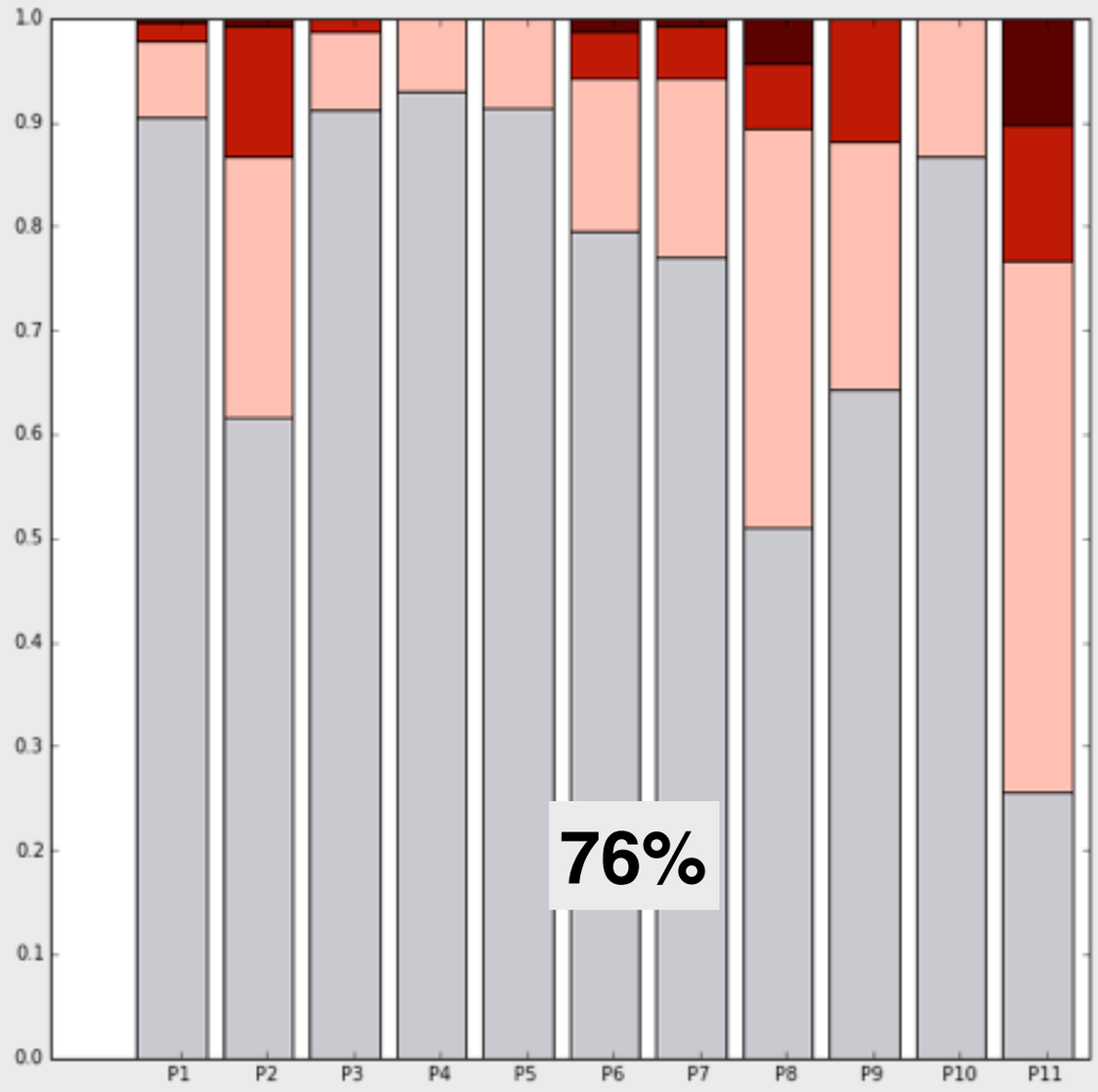
- **Comfort sensation can represent the intensity of discomfort, but no warm-cold direction information**
  People interpret “uncomfortable” as moment that they would take actions to adjust the temperature

Neutral & Comfort Report Dominate the Dataset

thermal sensation



comfort sensation



#reports of each individual

Participant	Gender	Valid	Household	House Size (sqft)	# Household Members
P1	F	**187**	H1	TH	4 Adults
P2	F	**98**	H1	TH	4 Adults
P3	M	**138**	H2	Apt	2 Adults
P4	F	**91**	H2	Apt	2 Adults
P5	M	**143**	H3	Apt	2 Adults*
P6	M	**131**	H4	Condo	2 Adults*
P7	F	**113**	H5	Apt	2 Adults
P8	F	10	H6	TH	2 Adults, 1 Child
P9	M	2	H6	TH	2 Adults, 1 Child
P10	M	**107**	H7	TH	2 Adults, 1 Dog
P11	F	**112**	H7	TH	2 Adults, 1 Dog