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Outdoor Thermal Comfort under Photovoltaic Canopies

A Seasonal Field Study at Arizona State University

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Phoenix Climate

- **Mild winters**

  average high temperatures between 19°C and 22°C from December to February

- **Hot summers**

  average high temperatures over 38°C from June to August

- **Annual average rainfall of 8 inches**

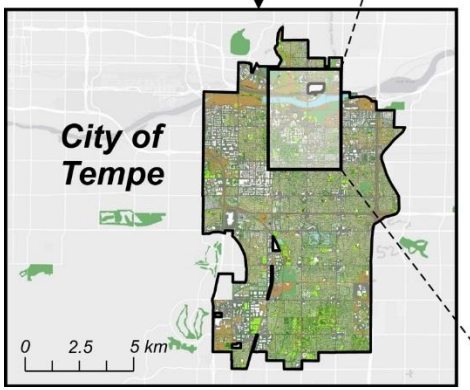
Heat Mitigation Strategies

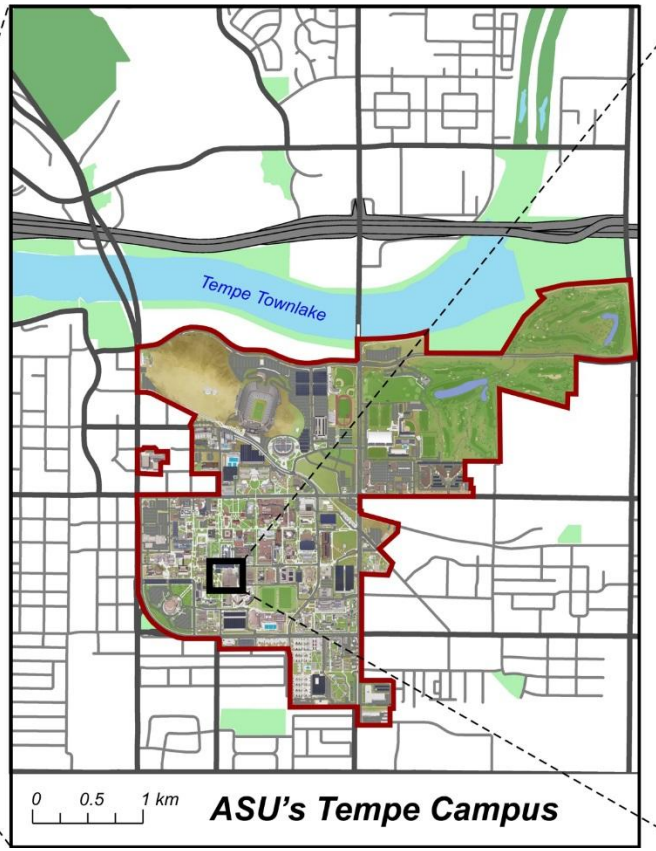
- **Urban fabric modification**
  - high surface albedo increases reflectivity and reduces heat absorption
- **Urban form modification**
  - density and height-to-width ratio of buildings alters ventilation
- **Urban Forest**
  - cools through shading and evapotranspiration
- ***Thermal comfort***
  - ***shade plays an important role in creating pedestrian-friendly outdoor spaces***

Research Goals

- **Quantify benefit of shade**
  - assess thermal comfort of shaded outdoor spaces vs. open spaces
- **Investigate relationship between perceived comfort and**
  - outdoor microclimate conditions
  - personal/psychological factors

Study Site: PV Canopy Structures

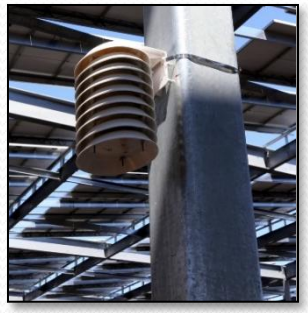




Photovoltaic Canopy at ASU's Memorial Union

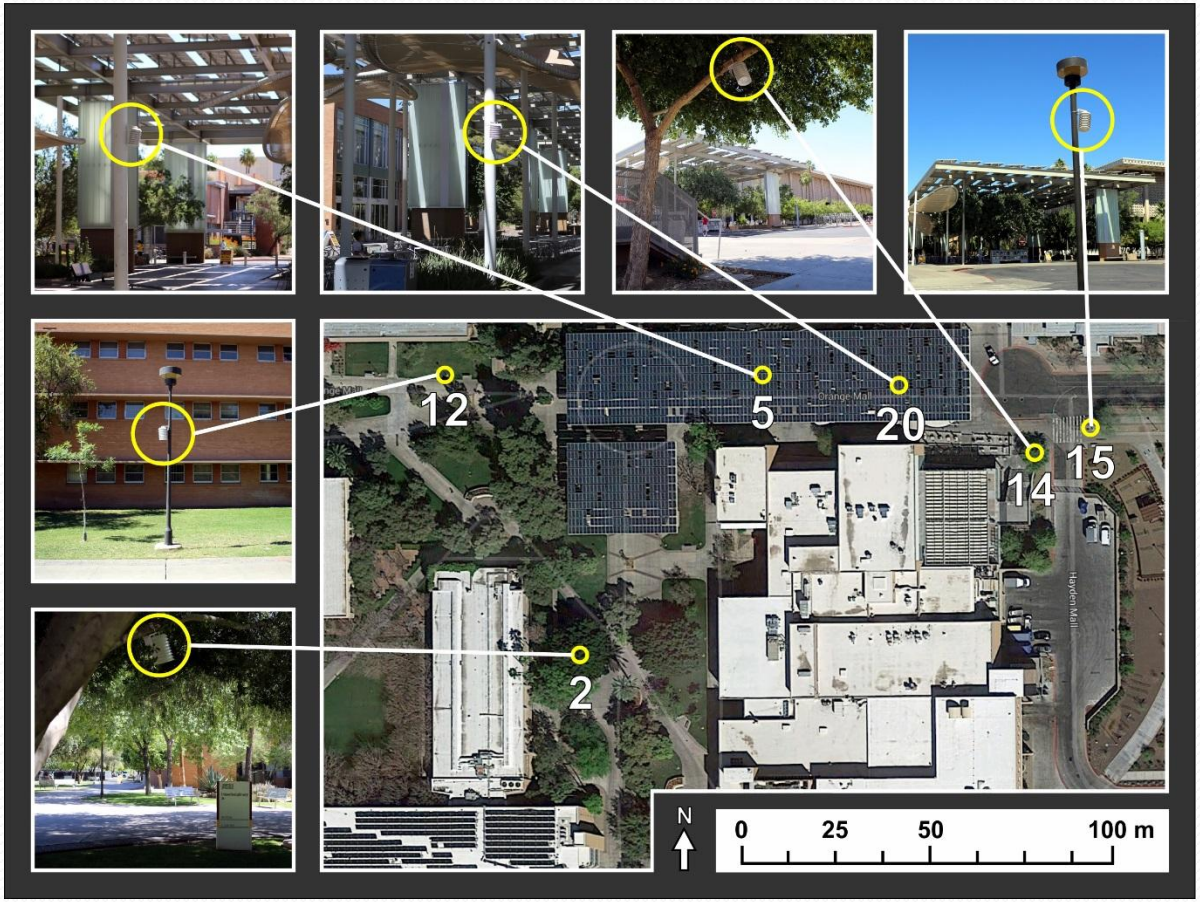
Experimental Design

- **Stationary sensors at 6 locations around the MU**
  - continuous measurement
  - every 5 minutes since June 4, 2014
  - shielded air temperature/humidity sensors



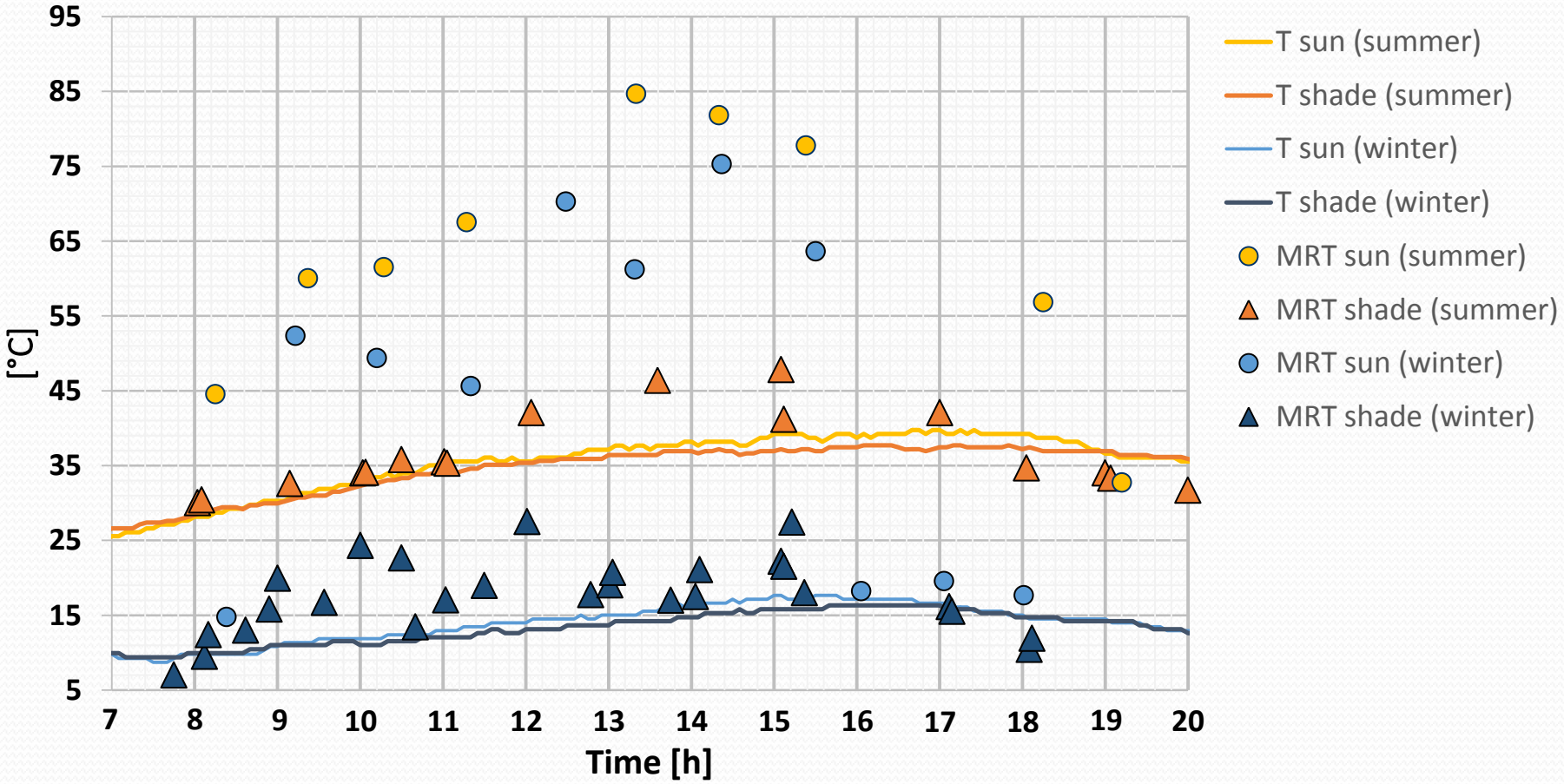
- **Sensor transects**
  - instantaneous measurements every hour (07:00h–22:00h)
    - pre-monsoon summer (June 10 and 19, 2014)
    - fall (November 11, 2014)
    - winter (January 22, 2015)
    - spring (April 2, 2015)
  - air temperature, humidity, wind speed, globe temperature, WBGT, solar radiation, surface temperature

Location of Stationary T/RH Sensors



Observed T and MRT (calculated from T_G)

June 19, 2014 and January 22, 2015



Field Survey Design

- **Questionnaire**
  - structured interviews
  - quasi-experimental design
    (subjects were not completely randomly chosen)
  - transversal survey
    (each person only participated once)
  - time to complete survey: 3 minutes
- **Time frame**
  - dates of sensor transects (1 day each season)
  - 08:00 AM to 06:00 PM

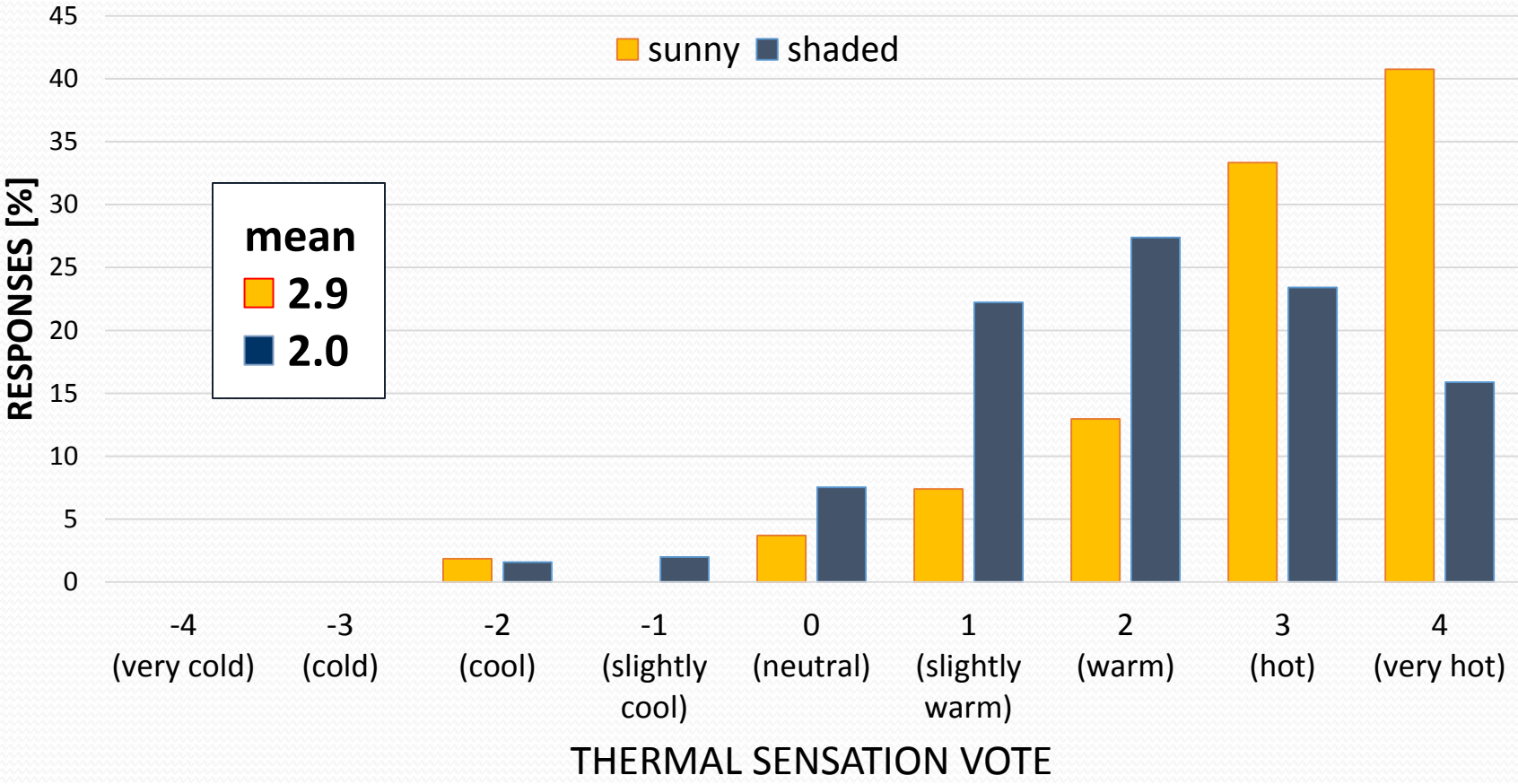
Thermal Comfort Survey

- Location
- Time
- General personal information
- Adaptation level
- Thermal comfort
- Thermal perception
- Short-term thermal history
- Activity level
- Thermal resistance of clothing
- Perceived control factor
- Temperature estimate

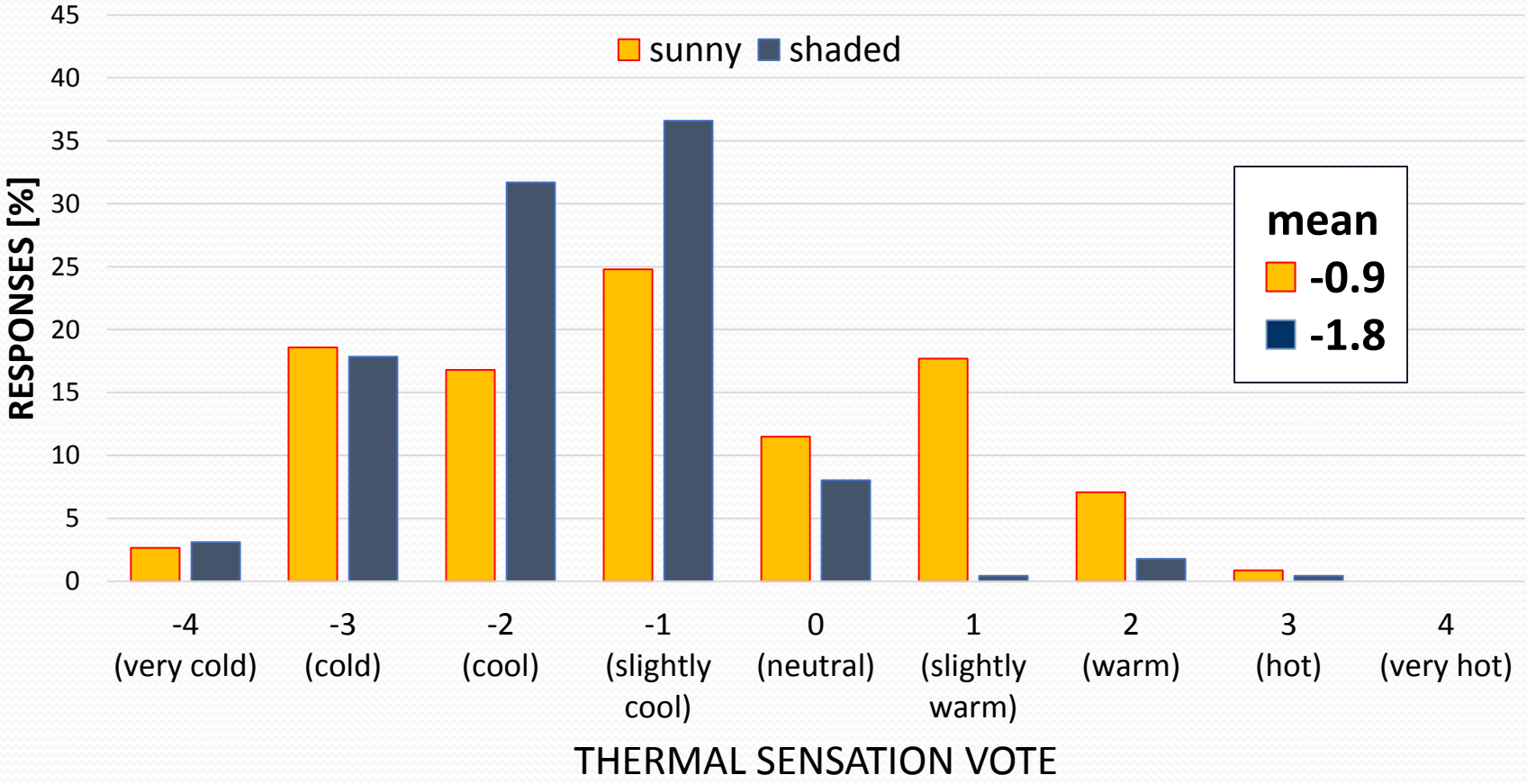
Survey Samples

		summer	fall	winter	spring
gender	male	184	224	189	159
	female	122	140	149	117
age	18–24	190	241	269	211
	25–34	61	67	54	37
	35–44	18	14	6	11
	45–54	14	18	6	8
	55–64	17	17	1	7
	65+	6	5	0	2
exposure	shade	252	270	225	225
	sun	54	94	113	51
N = 1284		306	364	338	276

Thermal Sensation Votes (TSV) - Summer



Thermal Sensation Votes (TSV) - Winter



Temperature Estimates

- **Summer**
  - ***full sun:*** respondents **overestimated** temperatures by 1.3°C ($\pm 0.6°C$)
  - ***shade:*** respondents **underestimated** temperatures by 1.6°C ($\pm 0.3°C$)
- **Fall**
  - ***full sun:*** respondents **overestimated** temperatures by 3.1°C ($\pm 0.4°C$)
  - ***shade:*** respondents got the temperature right! ($\pm 0.3°C$)
- **Winter**
  - ***full sun:*** respondents **overestimated** temperatures by 5.8°C ($\pm 0.4°C$)
  - ***shade:*** respondents **overestimated** temperatures by 2.6°C ($\pm 0.3°C$)
- **Spring**
  - ***full sun:*** respondents **overestimated** temperatures by 2.3°C ($\pm 0.5°C$)
  - ***shade:*** respondents **underestimated** temperatures by 1.0°C ($\pm 0.3°C$)

Analysis

- **Hourly meteorological observations were interpolated and linked to surveys based on time stamp**
- **Comparison of responses in the shade and in the sun**
  - T-test
- **Relationship between perceived comfort and climatic/non-climatic factors**
  - OLS and multiple regression

Sun vs. Shade

- **T-Test (all seasons)**
  - temperature*
  - surface temperature*
  - WBGT*
  - globe temperature*
  - incoming shortwave radiation*
  - net radiation*
  - MRT*
  - ~~relative humidity~~
  - ~~Heat index~~

* significant at the 0.01 level (2-tailed)

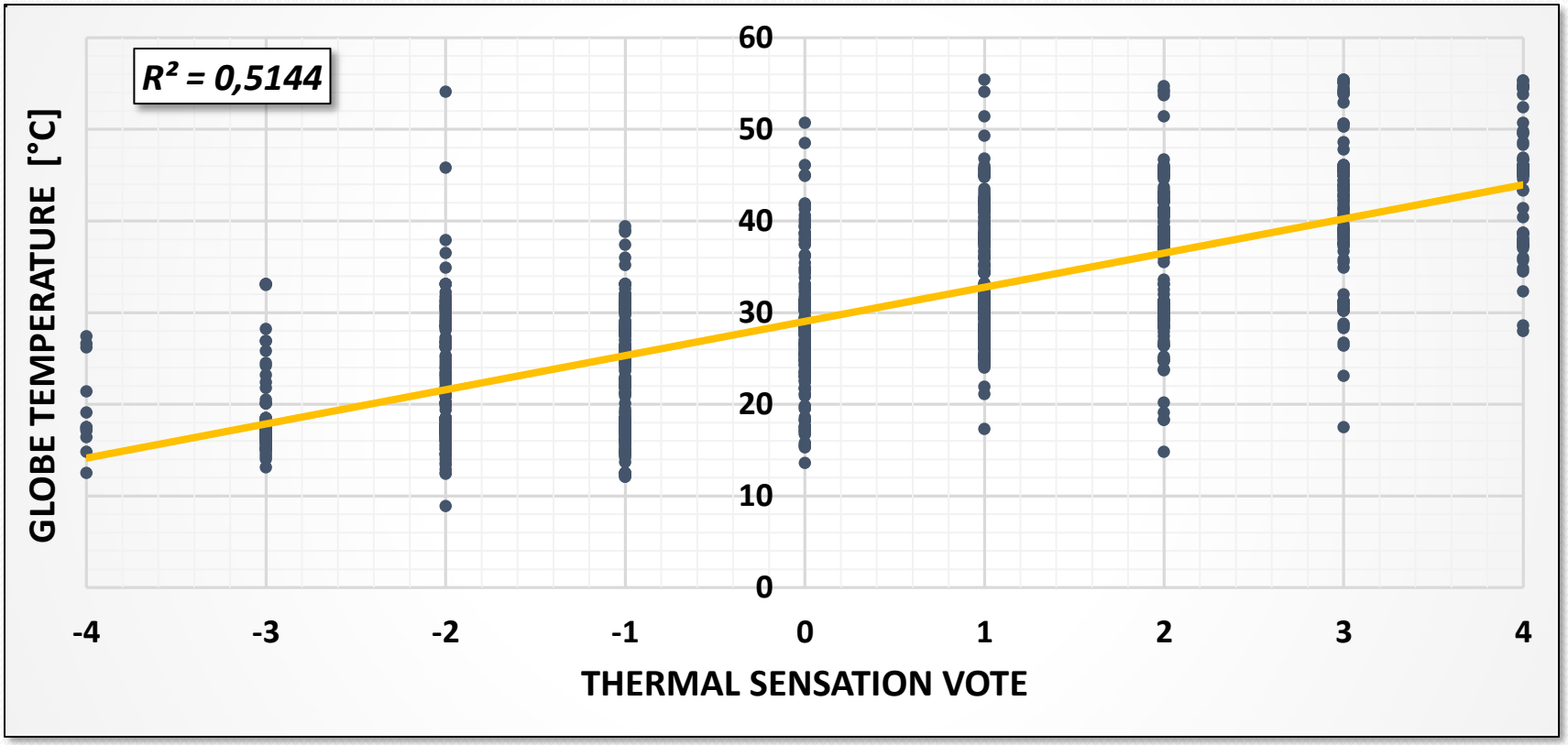
- **T-Test (split by season)**
  - thermal comfort (TSV*) varies significantly between sun and shade in the summer

Perceived Comfort and Microclimate

- **Multiple Regression (N = 1284, all seasons)**
  - dependent variable: ***TSV***
  - independent variables: ***meteorological observations***
    - air temperature and globe temperature significant at the 0.01 level
    - absolute humidity, surface temperature, incoming radiation, net radiation, and WBGT not significant

➡ ***globe temperature was the strongest predictor of perceived comfort***

Perceived Comfort vs. Globe Temperature



Perceived Comfort and Other Factors

- **Multiple Regression (N = 1284, all seasons)**
  - dependent variable: ***TSV***
  - independent variables: ***globe temperature*** and ***survey responses***
    - adaptation level, sun exposure, gender, metabolic rate (5mins), location choice, and clothing level significant at the 0.01 level
    - exposure to AC (5mins and 30 mins), metabolic rate (30 mins), age, and health-related mood not significant
  - Model improved from $R^2 = 0.51$ to $R^2 = 0.56$
  - F-test confirms that change in R^2 is significant

Summary and Future Work

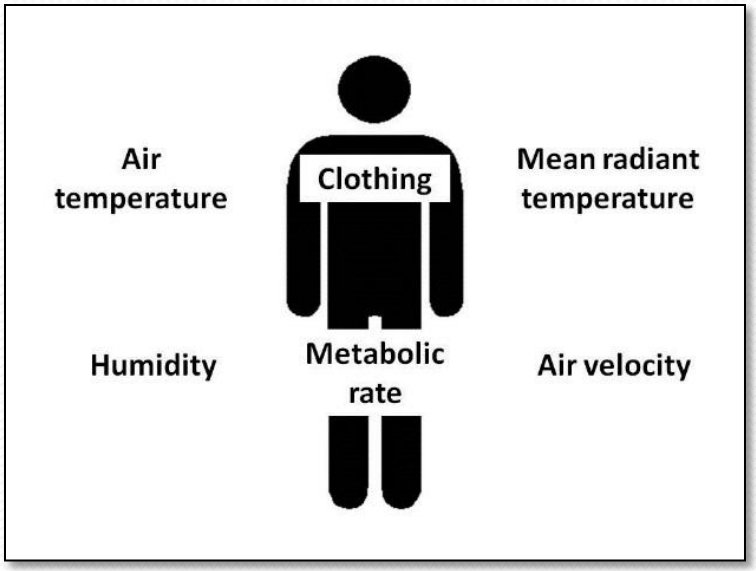
- **Shade vs. Sun**
  - in all seasons, photovoltaic canopy shade decreased TSV by ≈1 point on the Likert scale
  - in the summer, TSV varied significantly between shade and sun
  - respondents in the sun overestimated temperatures, but respondents in the shade underestimated temperatures in the summer and spring
- **Perceived comfort and climatic/non-climatic factors**
  - globe temperature explained about 50% of the variance in comfort
  - personal factors slightly improved the results (statistically significant)
- **Future Analyses**
  - more in-depth analysis of the impact of the relative importance of climatic and non-climatic factors
  - investigate relationships by season


Thank you!
Questions?

Thermal Comfort

"condition of mind that expresses satisfaction with the thermal environment; assessed by subjective evaluation" (ASHRAE Standard 55)

- **Main factors influencing thermal comfort**
  - **Environmental factors**
    - air temperature
    - mean radiant temperature
    - wind speed
    - relative humidity
  - **Personal factors**
    - metabolic rate
    - clothing insulation
  - **Psychological factors**



Sensor Specifications

Sensor	Variable(s)	Range	Accuracy	Height
LASCAR electronics EL-USB-2+ (shielded)	temperature	-35° to +80°C	± 0.3°C	2.6 m
	humidity	0% to 100% RH	± 2.0% RH	
Kestrel 4400	temperature	-10° to +55°C	± 0.5°C	1.1 m
	humidity	0% to 100% RH	± 3.0% RH	
	globe temperature	-10° to +55°C	± 1.4°C	
	WBGT	see temperature	± 0.7°C	
	wind speed	0.6 to 60.0 ms^{-1}	larger of 3% of reading, least significant digit or 20 ft/min	
DeltaTRAK 15002	surface temperature	-40° to 510°C	± 2.0°C	1.1 m

Thermal Comfort Survey

Thermal Comfort Study

Thank you for consenting to participate in this thermal comfort study. We are assessing thermal comfort of pedestrians on the ASU campus. All survey responses will remain anonymous, confidential, and the results will be published in aggregated form only.

1. On the scale below, how do you feel today (health-wise)?

-2	-1	0	+1	+2
very bad	bad	fair	good	very good

2. How familiar are you with Phoenix summer climate?

very familiar	familiar	somewhat familiar	not familiar
☐ I have lived here all my life	☐ I have lived here for_____years	☐I have experienced a summer in the desert before	☐ I am visiting from _____

3. Your reason for being at this location is:

☐ just passing by	☐ meeting someone	☐ resting	☐ other: _____

4. Please indicate how you feel *temperature-wise* at this moment:

-4	-3	-2	-1	0	+1	+2	+3	+4
very cold	cold	cool	slightly cool	neutral	slightly warm	warm	hot	very hot

5. Please indicate your current *comfort level*:

0	1	2	3
comfortable	slightly uncomfortable	uncomfortable	very uncomfortable

6. Would you prefer the thermal environment in this location to be…

-3	-2	-1	0	+1	+2	+3
much cooler	cooler	slightly cooler	neither warmer nor cooler	slightly warmer	warmer	much warmer

7. Please indicate your current exposure to the sun:

☐ full sun	☐ shade (under tree) ☐ shade (under solar canopy structure)

8. Please estimate the current ambient temperature (in °F): _____

9. If you are currently in the *sun*, how much *cooler* do you think will it be in the shade? If you are currently in the *shade*, how much *warmer* do you think will it be in the sun? (temperature in °F): _____

10. Where were you/what were you doing…

… 5 minutes prior to being here:	… 30 minutes prior to being here:
☐ driving a car ☐ riding a bike ☐ walking around ☐ public transport ☐ exercising ☐ inside air-conditioned building ☐ other: _____	☐ driving a car ☐ riding a bike ☐ walking around ☐ public transport ☐ exercising ☐ inside air-conditioned building ☐ other: _____

11. Clothing (please check all that apply):

☐ shirt or blouse, short sleeves ☐ shirt or blouse, long sleeves	☐ shorts or skirt long ☐ pants or jeans	☐ sweater ☐ coat

12. Age group

☐ 18-24 ☐ 25-34	☐ 35-44 ☐ 45-54	☐ 55-64 ☐ 65+

13. Gender

☐ male
☐ female

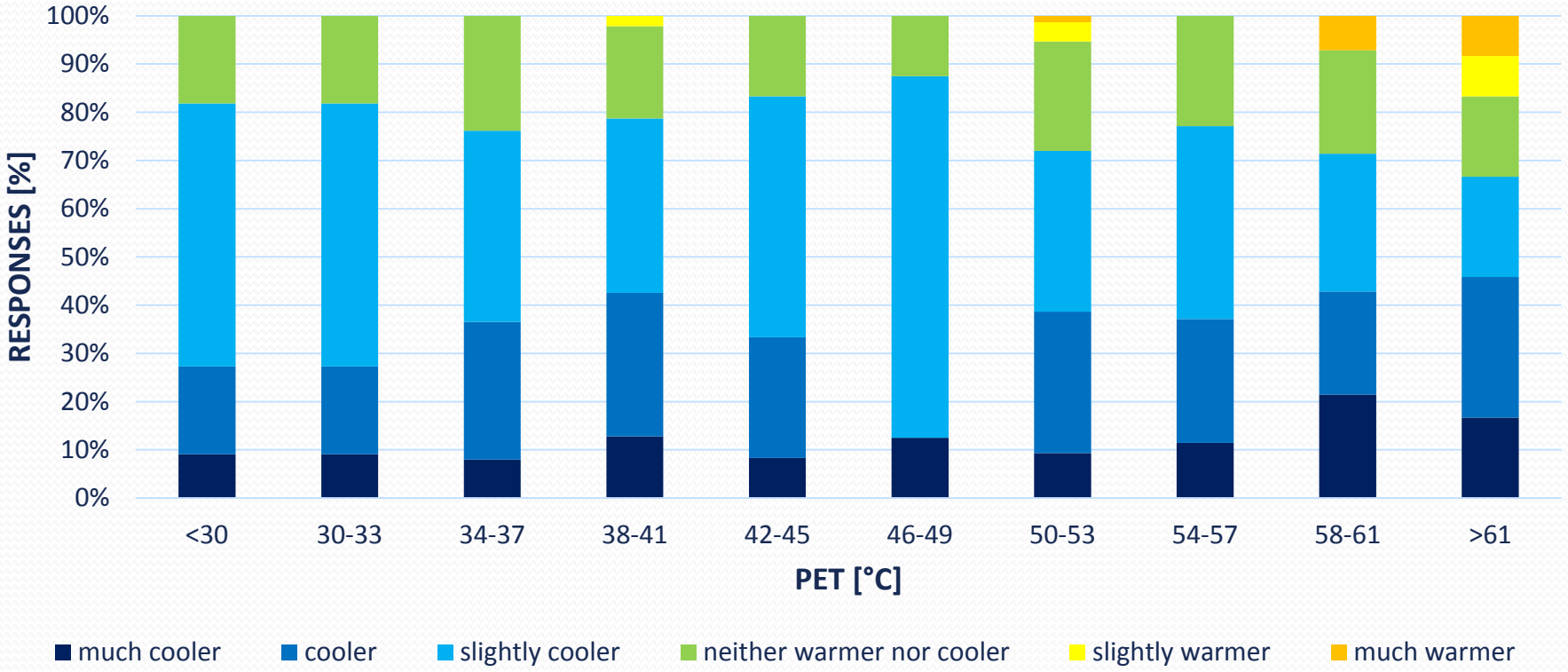
14. Current time: _____

	Thermal Perception		Thermal Comfort		Thermal Preference	
	r*	Sig. (2 tailed)	r*	Sig. (2 tailed)	r*	Sig. (2 tailed)
Age	-.194[3]	.001	-.154[3]	.007	.046	.420
Gender	-.084	.145	-.033	.285	.041	.477
Health Related Mood	-.185[3]	.001	-.228[3]	.000	.109	.058
Adaptation	-.286	.000	-.203[3]	.000	-.030	.601
Location Choice	-.085	.152	-.080	.170	.155[3]	.007
Current Exposure	-.153[3]	.007	-.102	.076	-.033	.563
AC/ No AC (5min ago)	-.165[3]	.004	-.249[3]	.000	.176[3]	.002
AC/ NO AC (30min ago)	.009	.878	-.051	.380	.033	.569
Metabolic Rate (5min ago)	.264[3]	.000	.303[3]	.000	-.126[2]	.028
Metabolic Rate (30 min ago)	-.038	.516	.047	.419	-.019	.748
Clothing	-.045	.433	-.062	.280	-.024	.672
WBGT	.324[3]	.000	.261[3]	.000	.036	.533
Heat Index	.291[3]	.000	.290[3]	.000	.037	.517
Globe Temperature	.360[3]	.000	.308[3]	.000	.022	.701
MRT	.327[3]	.000	.258[3]	.000	.030	.598
PET	.334[3]	.000	.263[3]	.000	.047	.410

Spearman's correlation coefficient

2 Correlation is significant at the 0.05 level (2-tailed)

3 Correlation is significant at the 0.01 level (2-tailed)


100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
RESPONSES [%]
<30
30-33
34-37
38-41
42-45
46-49
50-53
54-57
58-61
>61
PET [°C]
much cooler
cooler
slightly cooler
neither warmer nor cooler
slightly warmer
much warmer