Ear-Based Temperature Probing:
Sensor Placement and Fusion for Wearable Applications

Chair of Pervasive Computing Systems / TECO

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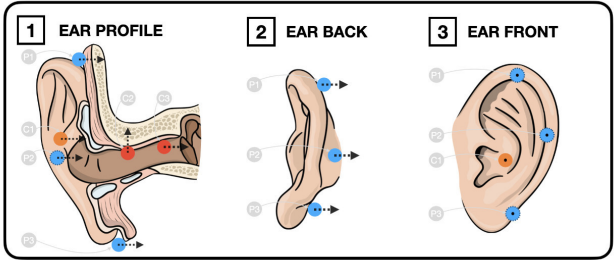
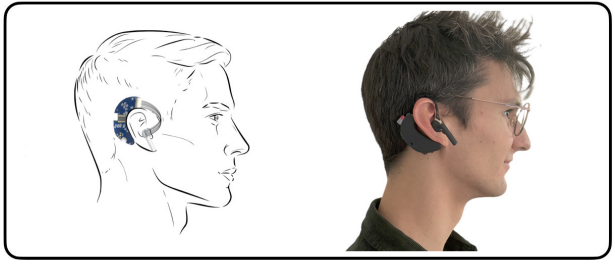




Motivation

- Current state of temperature measurement [2]
- No long-term measurement possible

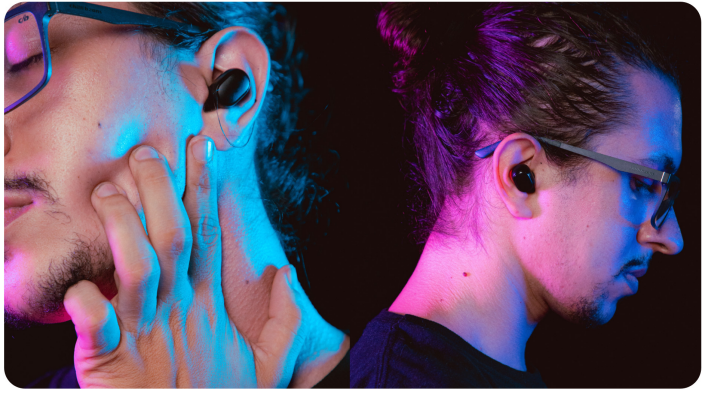
TYMPANIC MEMBRANE

RECTAL

ORAL

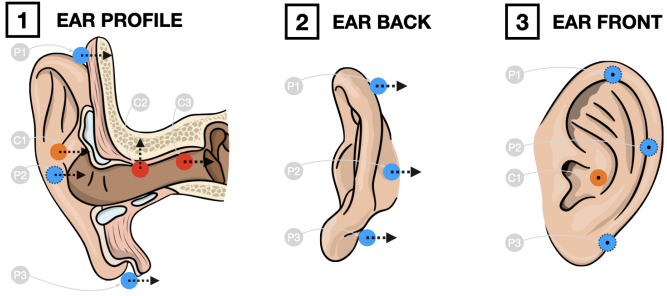
Motivation

- Solution: integration in wearables we already use a lot

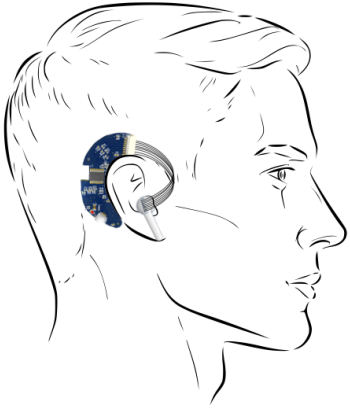


Planned Approach

- Device to measure ear-based temperature data
  - OpenEarable platform adaption
  - MLX temperature sensor
- 2 studies (baseline surveys and environmental influences, under stress conditions)

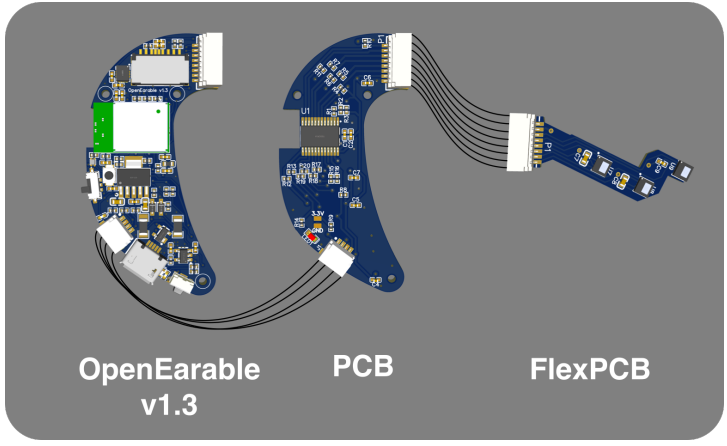


Prototype



Prototype: Main Hardware Connection

- Communication between components with I2C
- OpenEarable
  - SD card
  - Arduino Nano 33 BLE
  - IMU
  - Status LED
  - Clicky button
- PCB
- FlexPCB



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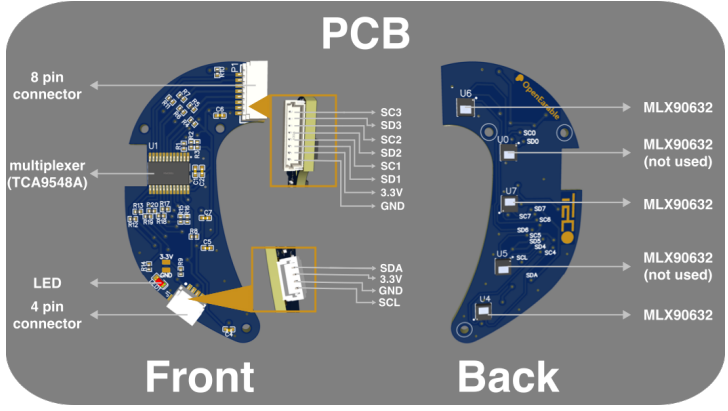
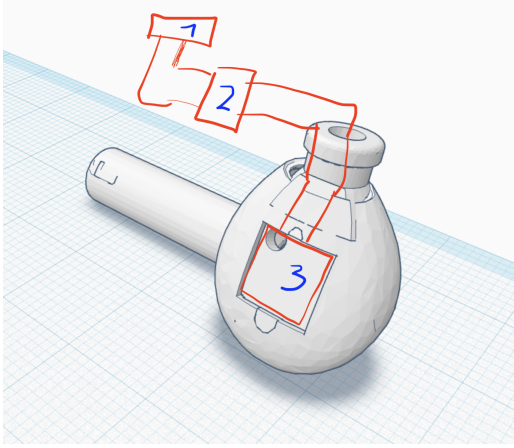
Institute of Telematics, Department of Informatics

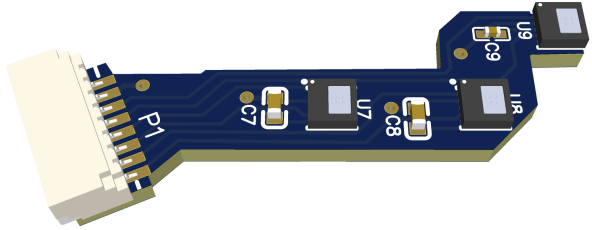
Prototype: PCB Composition

- 4-pin and 8-pin connector to connect OpenEarable and FlexPCB
- Multiplexer
  - Switch through one of 8 channels
  - Each temperature sensor is connected
- MLX90632 temperature sensor
  - Infrared sensor
  - Factory calibrated
  - Accuracy of $\pm 0.2^{\circ}$C
- LED

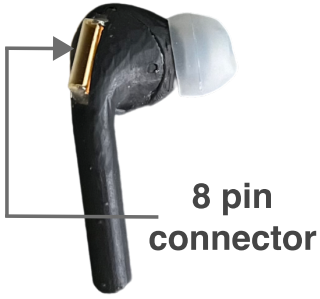


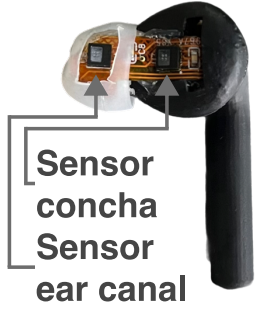
Prototype: FlexPCB - Concept vs Final Design





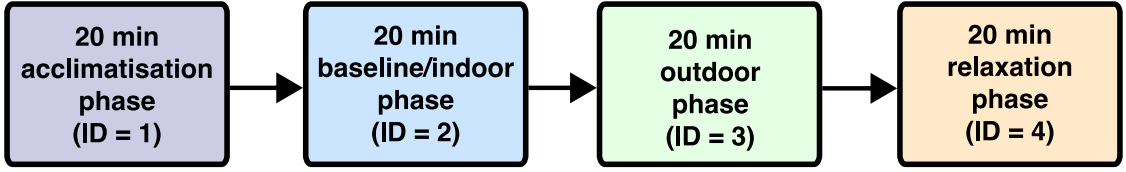
Prototype: FlexPCB

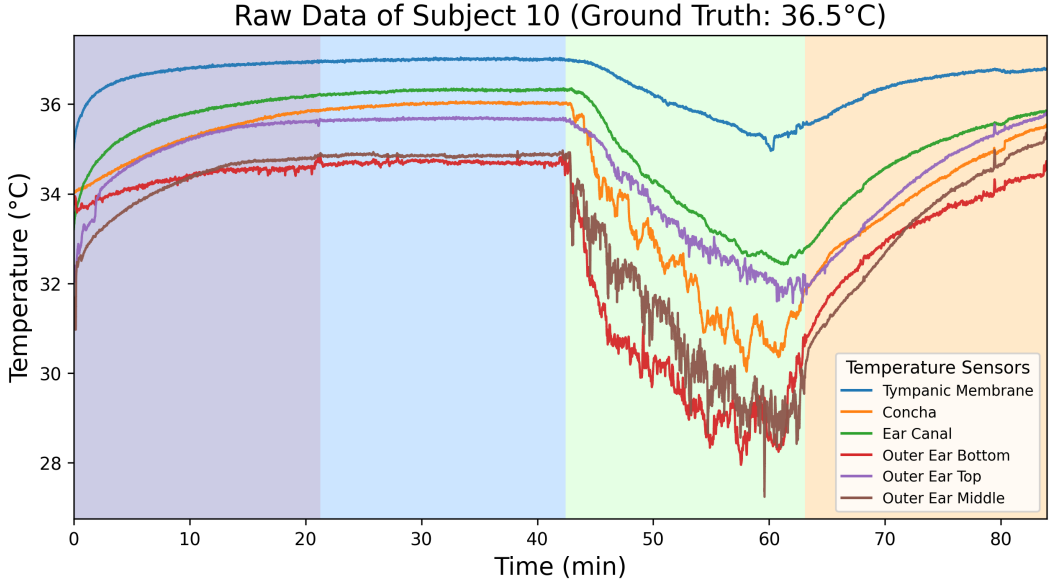




Study 1: Localized Ear Temperature Measurement Study Procedure: Baseline Surveys and Environmental Influences

- 12 probands (7 male, 5 female)
- Mean room temperature 25.4°C
- Mean outdoor temperature: 19.4°C
- Thermometer measurement before/after data measurement

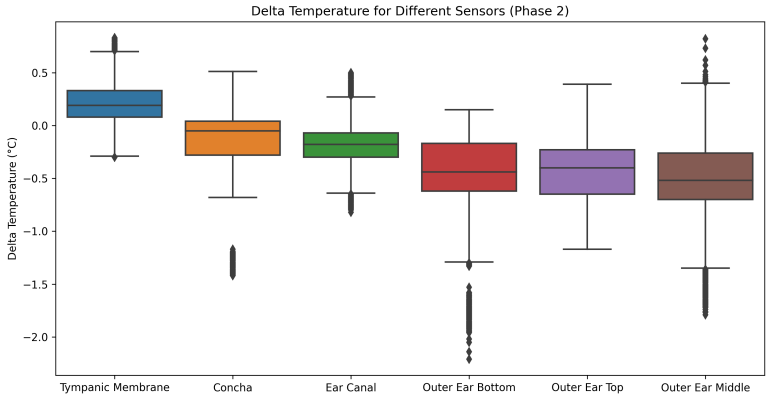



Raw Data of Subject 10 (Ground Truth: 36.5°C)
Temperature (°C)
Time (min)
Temperature Sensors
Tympanic Membrane
Concha
Ear Canal
Outer Ear Bottom
Outer Ear Top
Outer Ear Middle

Evaluation Study 1: Hypothesis 1

The temperature measured by sensors located behind the ear is lower compared to the other locations.

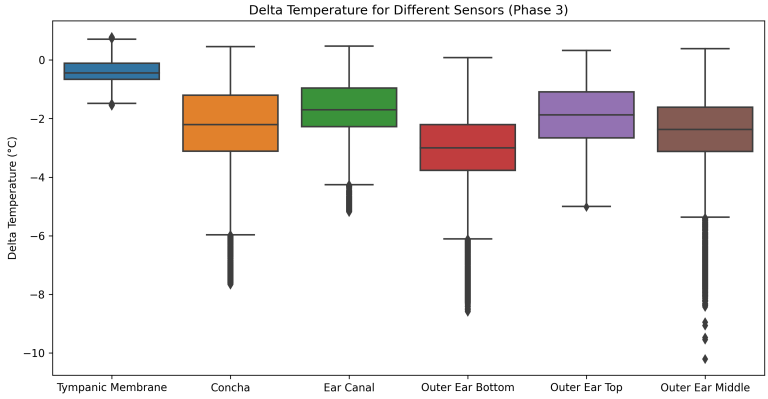
- Baseline phase (phase 2)
- Mean temperature of all probands
  - The ground truth is subtracted from each measured temperature value



Evaluation Study 1: Hypothesis 1

The temperature measured by sensors located behind the ear is lower compared to the other locations.

- Outdoor phase (phase 3)
- Mean temperature of all probands
  - The ground truth is subtracted from each measured temperature value



Evaluation Study 1: Hypothesis 2

The variance in temperature readings differs between indoor and outdoor settings

- Huge increase in variance between indoor and outdoor phase for each sensor position

Sensor	Mean Variance (in $°C^2$)	
	Indoor	Outdoor
Tympanic Membrane	0.00097	0.107
Concha	0.00307	1.134
EarCanal	0.00155	0.646
Outer Ear Bottom	0.01890	1.110
Outer Ear Top	0.00694	0.650
Outer Ear Middle	0.01980	1.098

Evaluation Study 1: Hypothesis 2

The variance in temperature readings differs between indoor and outdoor settings

- Null hypothesis is rejected, if $p < 0.05$.
- Strong indication that the hypothesis is proven.

Sensor	p-value
Tympanic Membrane	0.0005438
Concha	0.0005870
Ear Canal	0.0005009
Outer Ear Bottom	4.71×10^{-6}
Outer Ear Top	7.04×10^{-7}
Outer Ear Middle	0.0002436

Evaluation Study 1: Hypothesis 4

The temperature at the tympanic membrane has the greatest stability compared to other sensor locations

- The results for the outdoor area in particular show that the tympanic membrane is the most stable.

Sensor	Mean Standard Deviation Phase 2 (indoor)	Mean Standard Deviation Phase 3 (outdoor)
Tympanic Membrane	0.0308	0.3048
Concha	0.0535	0.9882
Ear Canal	0.0378	0.7496
Outer Ear Bottom	0.1138	1.0156
Outer Ear Top	0.0730	0.7836
Outer Ear Middle	0.1176	0.9875

Evaluation Study 1: Hypothesis 4

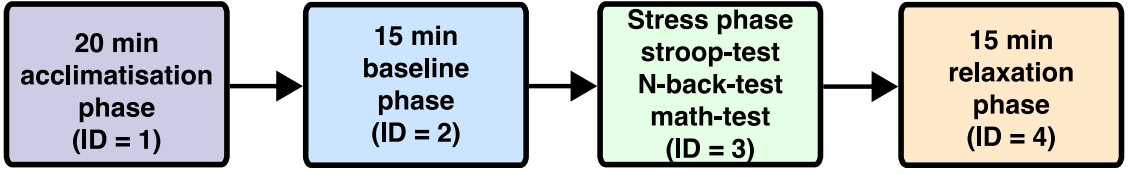
The temperature at the tympanic membrane has the greatest stability compared to other sensor locations

- Null hypothesis is rejected if $p < 0.05$.
- Strong indication that the hypothesis is proven.

Sensor	p-value
Tympanic Membrane	1.25×10^{-5}
Concha	9.39×10^{-6}
Ear Canal	5.96×10^{-6}
Outer Ear Bottom	2.09×10^{-7}
Outer Ear Top	6.59×10^{-8}
Outer Ear Middle	2.71×10^{-6}

Study 2: Study Course Under Stress Conditions: Impact on Temperature Measurements With Ear-Based Sensors

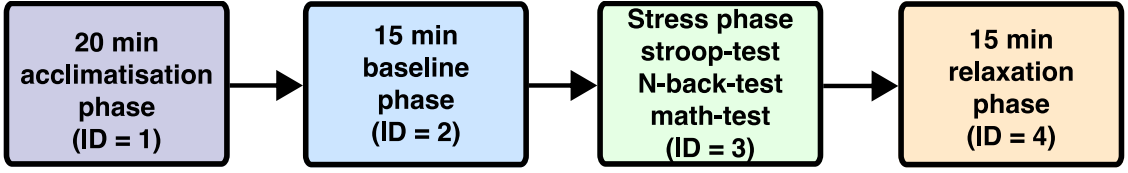
- 5 probands (3 male, 2 female)
- Mean room temperature 23.1°C
- Thermometer measurement before/after data measurement
- Polar H9 as ground truth for stress
- Significant temperature rise during stress [1, 3]

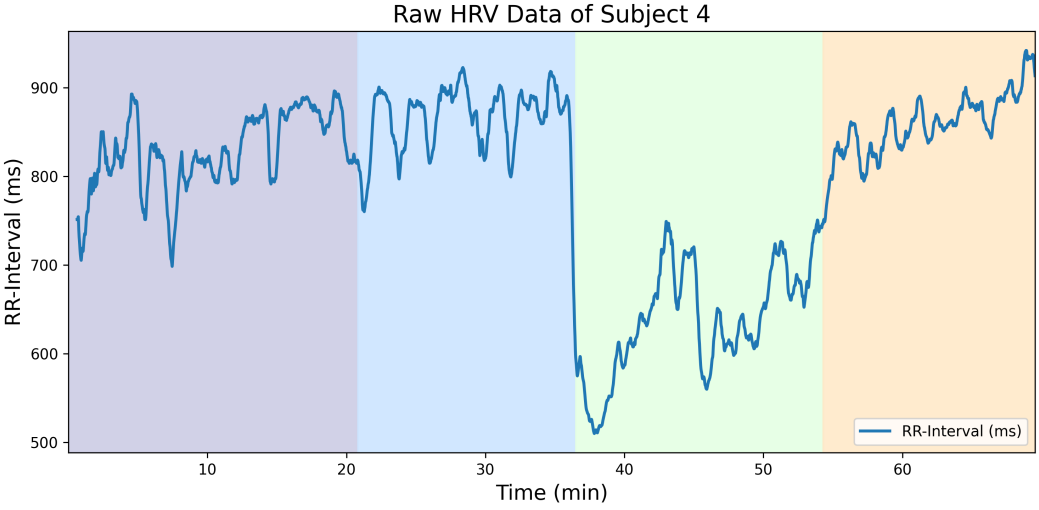


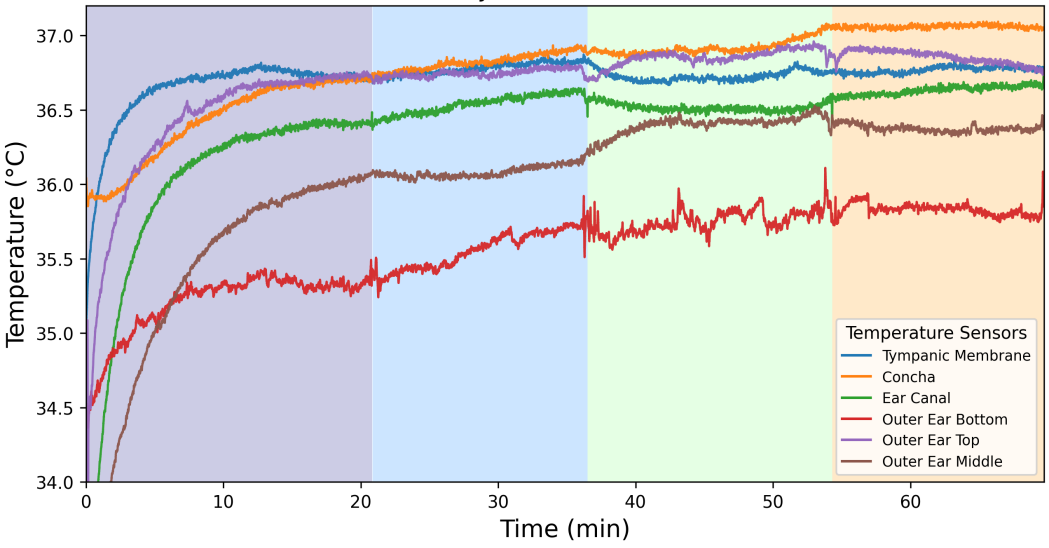
Study 2: Study Course Under Stress Conditions: Impact on Temperature Measurements With Ear-Based Sensors

Hypothesis:

- A measurable rise in temperature occurs during stress-inducing activities.
- There will be variability in temperature changes across different types of stress tests.




Raw HRV Data of Subject 4
RR-Interval (ms)
900
800
700
600
500
10
20
30
40
50
60
Time (min)
RR-Interval (ms)


Raw Data of Subject 4 (Ground Truth: 37.1°C)
Temperature (°C)
37.0
36.5
36.0
35.5
35.0
34.5
34.0
0
10
20
30
40
50
60
Time (min)
Temperature Sensors
Tympanic Membrane
Concha
Ear Canal
Outer Ear Bottom
Outer Ear Top
Outer Ear Middle

Conclusion

- Creation of a prototype
- 2 studies
  - Baseline and environmental influences
  - Under stress conditions
- Findings:
  - Prototype for future studies
  - Long-term temperature monitoring while sitting/ sleeping
  - High potential to include motion data

Future Work

- TSST for Stress Detection with Increased Sample Size
- Detection of Circadian Rhythm
- Early Detection of Disease
- Cycle Tracking for Women

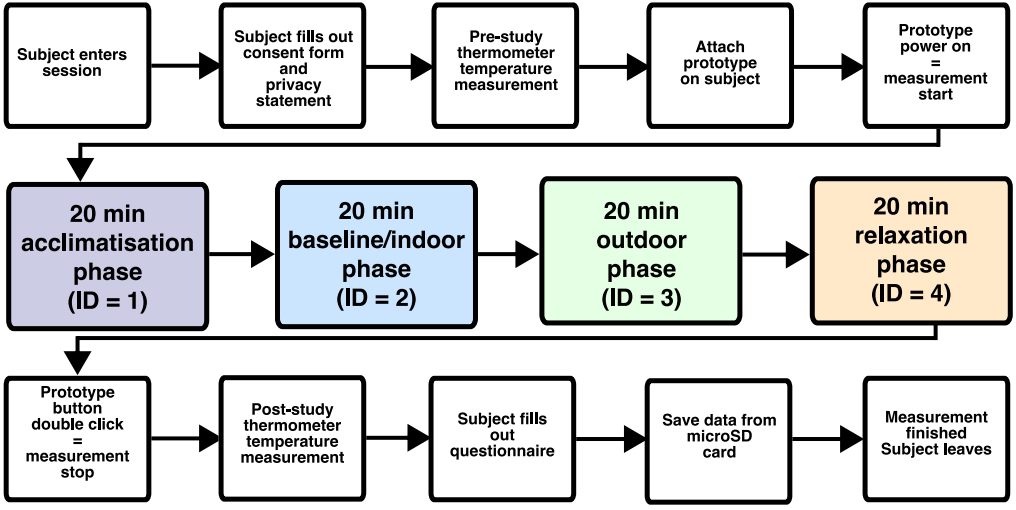
Literature

[1] Donatella Marazziti, Angela Di Muro, and Paolo Castrogiovanni. “Psychological Stress and Body Temperature Changes in Humans”. In: *Physiology & Behavior* 52.2 (Aug. 1992), pp. 393–395. ISSN: 0031-9384. DOI: 10.1016/0031-9384(92)90290-I. (Visited on 10/09/2023).

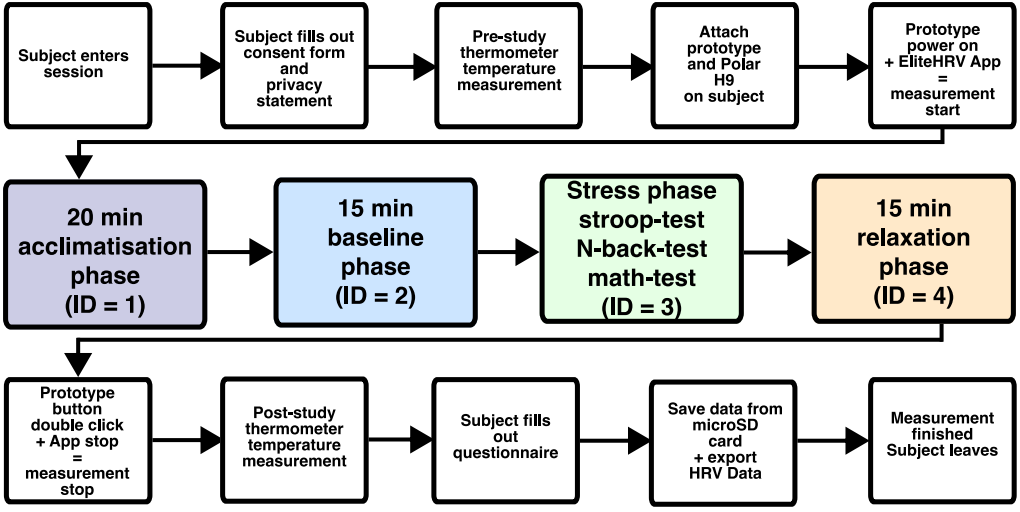
[2] *Temperature: Digital and Glass Thermometers*. https://www.nationwidechildrens.org/family-resources-education/health-wellness-and-safety-resources/helping-hands/temperature-digital-and-glass-thermometers. (Visited on 04/26/2023).

[3] Christiaan H. Vinkers et al. “The Effect of Stress on Core and Peripheral Body Temperature in Humans”. In: *Stress* 16.5 (Sept. 2013), pp. 520–530. ISSN: 1025-3890. DOI: 10.3109/10253890.2013.807243. (Visited on 10/09/2023).

Study 1: Localized Ear Temperature Measurement Study Procedure - Baseline Surveys and Environmental Influences



Study 2: Study Course Under Stress Conditions - Impact on Temperature Measurements With Ear-Based Sensors



Implementation

- Arduino code
  - setup() for initialization of temperature and IMU sensors and SD logger
  - loop() for measuring data (temperature sensors with $8,3Hz$, imu data with $50Hz$)
- Button action
  - Single click: next phase
  - Double click: stop measurement
- Store data on SD-card
  - 6 temperature sensors (object and sensor temperature)
  - IMU data
  - Timestamp
  - ID (phase)

Implementation

	ID	TIMESTAMP	TympanicMembrane	Concha	EarCanal	Out_Bottom	Out_Top	Out_Middle	ACC_X	ACC_Y	ACC_Z	GYRO_X	GYRO_Y	GYRO_Z	MAG_X	MAG_Y	MAG_Z
1	1	857	3499	0	0	0	0	0	-2673	97808	-12297	1219	12500	-4115	987000	-2325000	1083000
2	1	874	0	3403	0	0	0	0	-2775	98125	-12004	1829	13262	-4268	915000	-2373000	1107000
3	1	891	0	0	3320	0	0	0	-3056	97987	-12555	1753	15091	-4344	771000	-2421000	1095000
4	1	909	0	0	0	3386	0	0	-3235	98292	-12686	2820	15244	-5106	963000	-2397000	1083000
5	1	926	0	0	0	0	3234	0	-3786	98322	-13260	3353	15929	-6097	819000	-2277000	1083000
6	1	944	0	0	0	0	0	3142	-4007	97933	-13027	3429	14176	-7317	915000	-2205000	1089000
7	1	961	3499	0	0	0	0	0	-4521	97820	-13338	3811	13262	-6021	891000	-2373000	1083000
8	1	978	0	3403	0	0	0	0	-5365	98268	-14241	3734	11966	-4954	915000	-2325000	1071000
9	1	996	0	0	3320	0	0	0	-5664	98448	-14253	3277	9832	-5335	843000	-2397000	1089000
10	1	1013	0	0	0	3386	0	0	-5640	98382	-14301	3429	7164	-6631	843000	-2469000	1107000
11	1	1031	0	0	0	0	3234	0	-5359	97969	-14678	3277	6097	-6936	843000	-2205000	1083000
12	1	1048	0	0	0	0	0	3146	-5329	97886	-14768	2896	4954	-6402	939000	-2181000	1107000
13	1	1066	3507	0	0	0	0	0	-5120	98125	-14863	1981	4115	-4801	939000	-2253000	1077000
14	1	1083	0	3400	0	0	0	0	-4605	98538	-14211	838	3125	-3887	891000	-2205000	1083000
15	1	1100	0	0	3328	0	0	0	-4539	98472	-14702	533	3506	-4192	915000	-2397000	1071000
16	1	1118	0	0	0	3386	0	0	-4294	98185	-14008	152	3277	-3811	915000	-2205000	1101000
17	1	1135	0	0	0	0	3209	0	-3660	97844	-13852	-609	4573	-3658	723000	-2205000	1077000
18	1	1153	0	0	0	0	0	3146	-4157	97377	-14259	304	5411	-4420	915000	-2301000	1083000

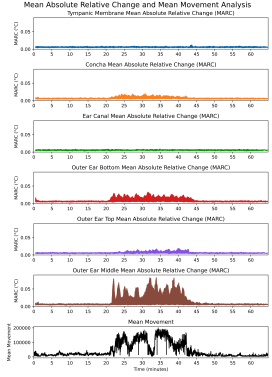
Evaluation Study 1: Hypothesis 3

Relative changes in temperature readings across different sensor locations will be interrelated.

Sensor	MAD (Indoor)	MAD (Outdoor)
Tympanic Membrane	0.025	0.258
Concha	0.042	0.820
EarCanal	0.030	0.624
Outer Ear Bottom	0.095	0.800
Outer Ear Top	0.062	0.663
Outer Ear Middle	0.101	0.831

Evaluation Study 1: Hypothesis 5

Subject movement leads to significant changes in the temperature readings across various sensor locations.



Stress Detection

Subj.	SDNN (ms)		RMSSD (ms)		LF/HF		Stress-Index		PNS Index		SNS Index	
	Base	Stress	Base	Stress	Base	Stress	Base	Stress	Base	Stress	Base	Stress
1	65.89	47.25	29.66	21.99	12.08	9.80	7	11	-1.6	-1.85	1.96	2.73
2	70.93	71.62	42.05	44.76	2.75	3.49	8	8	-0.92	-0.98	0.87	1.02
3	150.45	163.09	99.82	79.58	0.68	1.22	5	6	2.21	0.92	-1.33	-0.51
4	101.44	71.71	35.86	19.37	2.08	4.40	9	14	-0.51	-2.01	0.33	2.73
5	225.16	202.75	268.12	235.46	0.29	0.34	2	2	7.26	6.44	-2.28	-2.24

- **SDNN**: Standard Deviation of NN intervals - decrease under stress (individual)
- **RMSSD**: Root Mean Square of Successive Differences - decrease under stress
- **LF/HF**: Balance between parasympathetic and sympathetic activities - increase under stress (individual)
- **Stress Index**: The higher the value, the more stress the person has.
- **PNS Index**: Higher positive values indicate relaxation
- **SNS Index**: Higher values induce stress or fight-or-flight responses

Evaluation Study 2: Hypothesis 1

A measurable rise in temperature occurs during stress-inducing activities.

Subject	Tympanic Membrane (in °C)	Concha (in °C)	EarCanal (in °C)	Outer Ear Bottom (in °C)	Outer Ear Top (in °C)	Outer Ear Middle (in °C)
1	-0.04	-0.0	-0.08	0.25	0.11	0.19
2	-0.01	0.20	0.16	0.14	0.10	0.27
3	0.00	0.21	0.17	0.15	0.12	0.02
4	-0.05	0.10	-0.02	0.20	0.11	0.32
5	-0.04	0.00	-0.04	0.05	0.03	0.11

Temperature difference from baseline to stress-induced for each participant.

Evaluation Study 2: Hypothesis 1

A measurable rise in temperature occurs during stress-inducing activities.

Subject	Tympanic Membrane (in °C)	Concha (in °C)	EarCanal (in °C)	Outer Ear Bottom (in °C)	Outer Ear Top (in °C)	Outer Ear Middle (in °C)
1	-0.02	-0.08	-0.07	-0.15	-0.04	-0.04
2	0.0	0.14	0.16	0.07	0.04	0.14
3	-0.03	0.1	0.11	0.28	0.02	0.11
4	0.04	0.14	0.12	0.08	0.0	-0.02
5	-0.15	-0.12	-0.13	-0.11	-0.06	-0.07

Temperature difference from stress-induced to relaxation for each participant.

Evaluation Study 2: Hypothesis 2

There will be variability in temperature changes across different types of stress tests.

Subject	Tympanic Membrane (in °C)	Concha (in °C)	EarCanal (in °C)	Outer Ear Bottom (in °C)	Outer Ear Top (in °C)	Outer Ear Middle (in °C)
1	0.00	0.03	-0.02	0.05	0.03	0.02
2	-0.01	0.06	-0.03	0.07	-0.01	0.11
3	-0.01	0.05	0.02	0.04	0.09	0.05
4	-0.08	-0.01	-0.06	0.04	0.11	0.16
5	-0.02	0.03	-0.02	0.09	0.05	0.06

Temperature differences between Stroop and N-Back for each participant.

Evaluation Study 2: Hypothesis 2

There will be variability in temperature changes across different types of stress tests.

Subject	Tympanic Membrane (in °C)	Concha (in °C)	EarCanal (in °C)	Outer Ear Bottom (in °C)	Outer Ear Top (in °C)	Outer Ear Middle (in °C)
1	-0.06	-0.01	-0.05	0.03	0.02	0.05
2	-0.03	0.09	0.10	0.00	0.05	0.11
3	0.03	0.12	0.11	0.10	0.13	0.13
4	0.02	0.03	-0.01	0.06	0.01	0.02
5	-0.03	-0.04	-0.07	0.07	-0.01	0.02

Temperature differences between N-Back and Math for each participant.