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A low-cost measurement device for recording perceptions of thermal comfort

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Abstract. In this article, we describe the implementation of a low-cost device that registers perceptions of thermal comfort. The parameters of relative humidity (RH), temperature, thermal sensation (cold, cool, neutral, warm, hot) and clothing worn by people are collected. The design and validation of the device in an indoor environment are explained, and the calibration curves of the temperature and relative humidity sensors are obtained. The measurement results for the device from 10 people are shown. The study was carried out in the village of Imata (high Andean zone), at 4700 masl in the south of Peru.

1. Introduction

Thermal comfort is defined as a satisfactory perception of the thermophysical relationship of a person with his environment. Various ways of evaluating that perception have been proposed. For example, in the international standard ISO 7730 [1], comfort is defined as a condition of mind marked by satisfaction with the thermal environment. Dissatisfaction can be caused by warm or cool discomfort of the body as a whole or by an unwanted cooling (or heating) of one particular part of the body. Due to individual differences, it is impossible to specify a thermal environment that will satisfy everybody. There will always be a percentage of dissatisfied occupants.

Thermal sensation is understood as a sensory experience – a psychological response to the state of thermoreceptors in a human body, as discussed in detail, for example, by Parsons [2]. Because of this response, thermal sensation describes how a person feels thermally, e.g., ‘slightly warm’. Thus, such assessments should be free of any affective information because the information needed is ‘how do you feel’ (e.g., ‘slightly warm’) not ‘how do you find it’ (e.g., ‘comfortable’). The thermal sensation scale is commonly used as a categorical scale; i.e., subjects can only choose verbal markers between ‘cold’ and ‘hot’, but nothing in between [3].

Previous studies of thermal comfort differ in the methods used, the duration of the monitoring period and the season in which the measurements were made. In some studies, the data were collected locally with data loggers [4–[6], while other studies used questionnaires or diaries [7] to record temperatures, and study participants had to fill in the required information, as no measurements were performed [8].



This can lead to large uncertainties. In addition, studies that use a combination of both types of data (qualitative and quantitative) can be found [8-10].

Ioannou et al. [8] developed a device for wirelessly collecting quantitative data inside dwellings. In addition, they collected qualitative data (thermal sensation, metabolic activity, clothing and activities during the previous half hour) through manual entries. This data collection allowed the thermal sensations of the individuals who inhabited the dwellings to be correlated in time with the ambient conditions (temperature, relative humidity and CO₂ level). All data were available for inspection and analysis in real time throughout the assessment through a remote desktop application.

Similarly, data recording devices have been developed for climate data monitoring; for example, Karami et al. [5] developed a device that includes sensors for temperature, relative humidity, illuminance, CO₂, VOC, and PM_{2.5} to measure the indoor Environmental Quality of Environments (IEQ). The thermal comfort, indoor air quality and lighting performance were analysed with the collected data.

Carre et al. [6] described the design of an environmental data recording device and presented the early results of the validation. Ali et al. [11], Ferrero et al. [12], Bamodu et al. [13], and Ferdoush et al. [14] developed low-cost devices for measuring environmental parameters.

The advantage of using data loggers that collect both types of information (qualitative and quantitative) is that data are recorded even in the absence of the researchers. Thus, when developing a data logger device, we decided to evaluate the validity of the main known methods for this type of peculiar environment that brings together the climate and topography of South America, including its high altitude and rural areas. We also decided that we would design a new characterisation/estimation method if necessary.

The implemented device consists of a real-time measurement recorder of quantitative and qualitative parameters to be used in field studies in Imata, San Antonio de Chuca district, Caylloma province, Arequipa region in Peru at 4700 masl.

2. Methodology

This article covers the initial design of the circuit (made in KiCad [15]), the construction of the device, the verification of its correct operation, and its calibration and application in indoor test environments. The programming was done using the Arduino IDE [16], which is a free software. Finally, the first results collected in Imata are presented.

2.1. Description and design of the device

Our device registers 7 parameters: time-date, temperature, relative humidity, thermal sensation (very cold, cold, neutral, hot, very hot), personal information (linear selector of 6 positions), clothing (9 push-buttons with the characteristic clothes worn by inhabitants of the area) and battery voltage. A push-button called "SAVE" was installed, and as long as it is not pressed, the data will not be recorded in the memory device.

The algorithm of the operation of the device is explained in figure 1. The device uses the Atmega328P microcontroller, which is programmed to remain in sleep mode (power save mode) when the device is not being used. The microcontroller works in parallel on two sides: the first corresponds to the clock chip, and the second operates when some push-button on the device is pressed.

The clock has an output that generates a square wave signal of 1 Hz. Once it is set to high, the timer increases by 1 second. The next part is to determine whether the current time is between a certain time range (for example, a start time of 6:00 a.m. and an end time of 7:00 p.m.). Within that interval, the question "was any push-button pressed during the last one-hour interval?" is asked. If no information was recorded, an alarm is activated (during 5 seconds) as a reminder for people to use the device. If users register data during the last hour, the alarm is not activated.

In parallel, when a push-button is pressed, the device begins to look for the push-button through the following questions: (a) "Was any thermal sensation push-button pressed?", and with an affirmative answer, the last push-button pressed is recorded; (b) "Was any push-button of clothing pressed?", and with an affirmative response, the counter corresponding to each push-button increases; (c) "Was the

delete push-button pressed?”, and when the answer is affirmative, the counter of the last deleted push-button of clothing is reset to zero, and (d) “Was the save push-button pressed?”, and when the answer is affirmative, the microcontroller reads all the previous information together with the other parameters (time and date, temperature, relative humidity, personal information and battery voltage), and then the information is transferred to the microSD card.

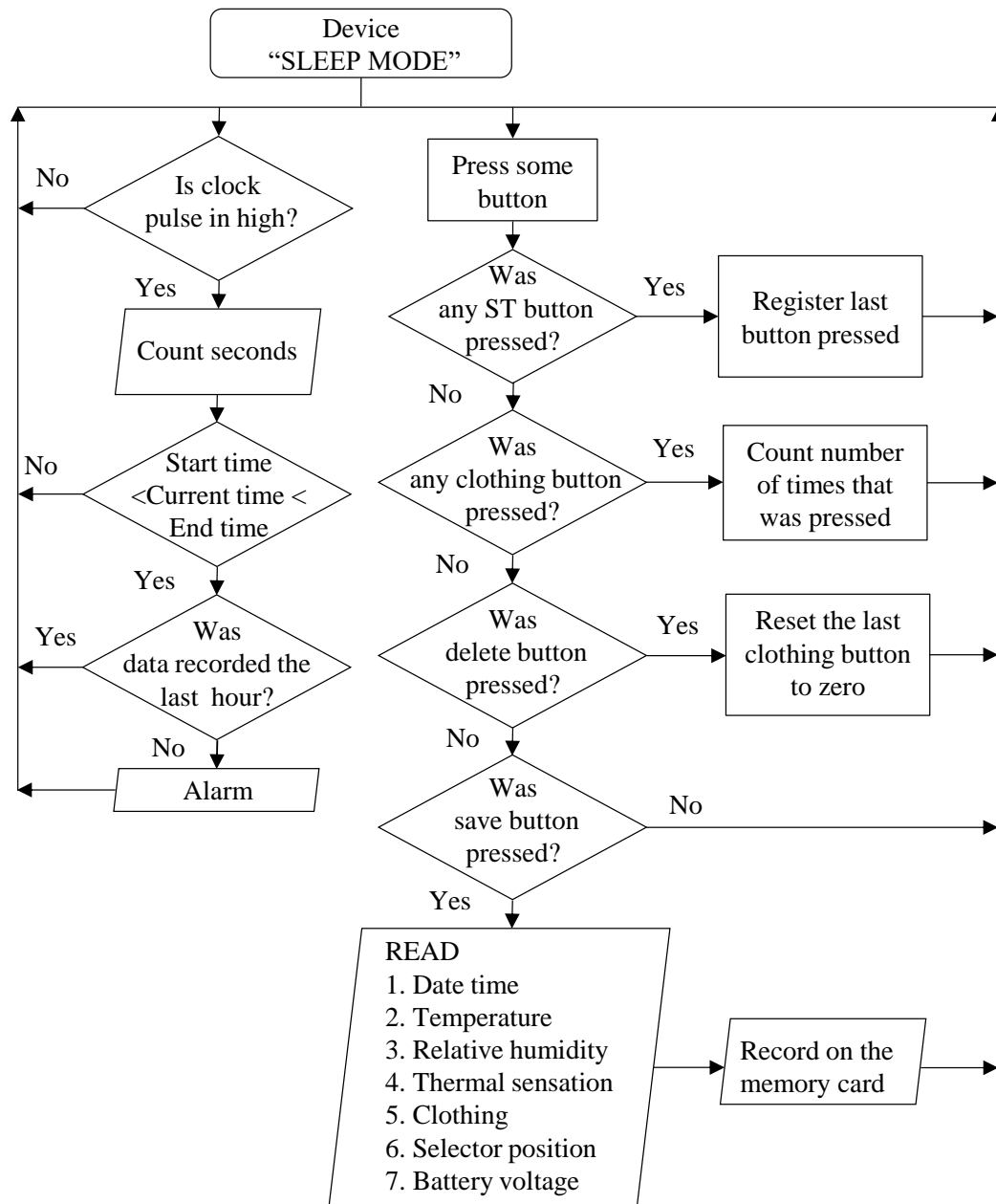


Figure 1. Algorithm of the operation of the device.

Each device has a 6-position linear selector that allows the registration of people who live in the same dwelling. Each position indicates a member of the family who is recording measurements. The design of the printed circuit was developed in the KiCad programme (previously it was implemented in a protoboard to verify correct operation). Two plates were designed: one with a double-side copper clad laminate glass fibre board and the other with a single-side copper clad laminate Bakelite board. Figure

2 shows the scheme made in the KiCad software. The circuit heat transfer process was carried out on both plates.

The characteristics of the components are illustrated in table 1. The temperature sensor has an accuracy of ± 0.5 °C, and the relative humidity sensor has an accuracy of 2-5%. The DHT22 sensor, a low-cost digital temperature and humidity sensor, is used in the device.

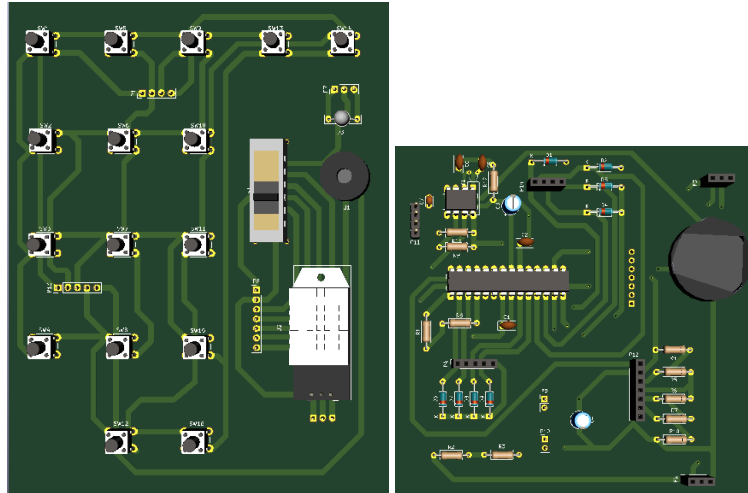


Figure 2. Design of the two plates of the device, made in KiCad.

Table 1. Device specification.

Component	Characteristic
DHT22 temperature and humidity sensor [17]	<ul style="list-style-type: none"> ▪ 3 to 5 V power and I/O ▪ 2.5 mA max current use during conversion ▪ Good for 0-100% humidity readings with 2-5% accuracy ▪ Good for -40 to 80°C temperature readings ± 0.5°C accuracy
Atmega328P microcontroller [18]	<ul style="list-style-type: none"> ▪ 8-bit ▪ Operating voltage: 1.8 - 5.5 V ▪ I/O and Packages - 23 Programmable I/O Lines ▪ Flash memory 32 KB ▪ SRAM 2 KB and EEPROM 1 KB
DS1307 serial real-time clock	<ul style="list-style-type: none"> ▪ 56-Byte, battery-backed, general-purpose RAM with unlimited writes ▪ I²C serial interface ▪ Programmable square-wave output signal ▪ Consumes less than 500 nA in battery backup mode with oscillator running ▪ Temperature Range: -40°C to +85°C ▪ 8-Pin DIP minimises required space
Others	<ul style="list-style-type: none"> ▪ MicroSD card, micro switch (6x6x8 mm), slide switch (six positions), buzzer (5 V working voltage), resistors, capacitors, RGB LED, oscillator, diodes, battery holder, switch, wire, connectors and support box.

The device was designed to store information on a microSD card in csv format. The required power is 4.5 V, and internally, there is a CR2032 battery as a backup for the clock.

The investment for the implementation of the device is around \$ 40, and each of the components can be purchased in the local market. This budget does not include assembly, which is assumed to be completed

by the researcher. All the components are contained in a plastic enclosure case of 0.10x0.15x0.07 m (see figure 3).

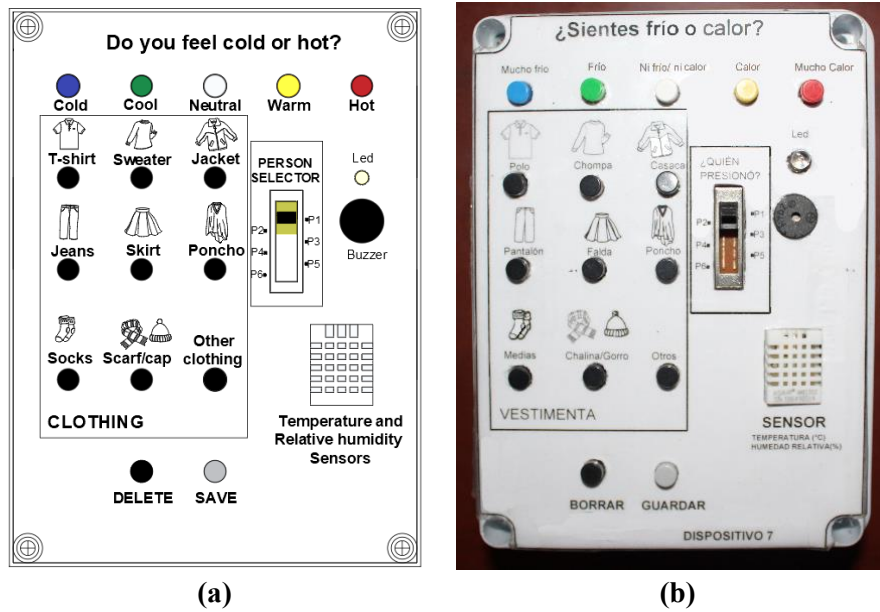


Figure 3. (a) Drawing, (b) front side of the implemented device.

3. Results and discussion

3.1. Calibration

The implemented device was compared with the measurements made with the Elitech GSP-6 sensor in a warm climate. Likewise, the DeltaOhm HD 32.3 device was used for comparison in a cold climate. The measurements were made inside a house. The reference instruments were mounted close to the logger sensor but not so close that they interfered with one another.

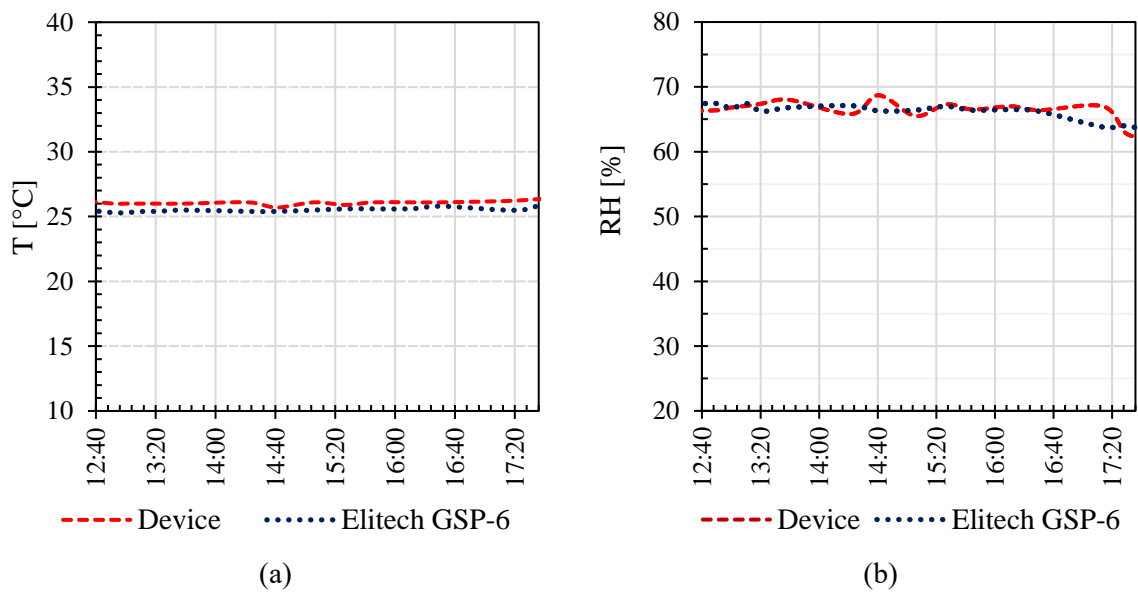


Figure 4. The implemented device and the sensor Elitech GSP-6. (a) Temperature sensor and (b) relative humidity sensor.

The warm weather measurements (in the month of December in the city of Lima) were carried out during 5 hours (see figures 4a and 4b). Due to the variations of temperature and relative humidity in the environment, very few units were recorded. Although a proper calibration was not performed, the trend of the curves can be seen. With the exception of some points, as in figure 4a, peaks can be observed at approximately 14:40 and 17:20 due to external factors, such as natural ventilation of the environment, and these peaks can be explained by the geometry of the sensor used. The Elitech temperature sensor has a cylindrical shape, and it is exposed to direct air currents, while the DHT22 sensor is inside a small enclosure with holes, and the air currents are not immediately perceived. In the case of figure 4b, the relative humidity sensor is more exposed to the environment than the DHT22 sensor, and in this case, the peaks can be attributed to the presence of a person who was in the environment during the measurements. Average differences of 0.6 °C and 1.8% were obtained for the relative temperature and humidity during the measurement period.



Figure 5. Photographs of DeltaOhm HD 32.3 and implemented devices in an indoor environment at the time of calibration in the village of Imata.

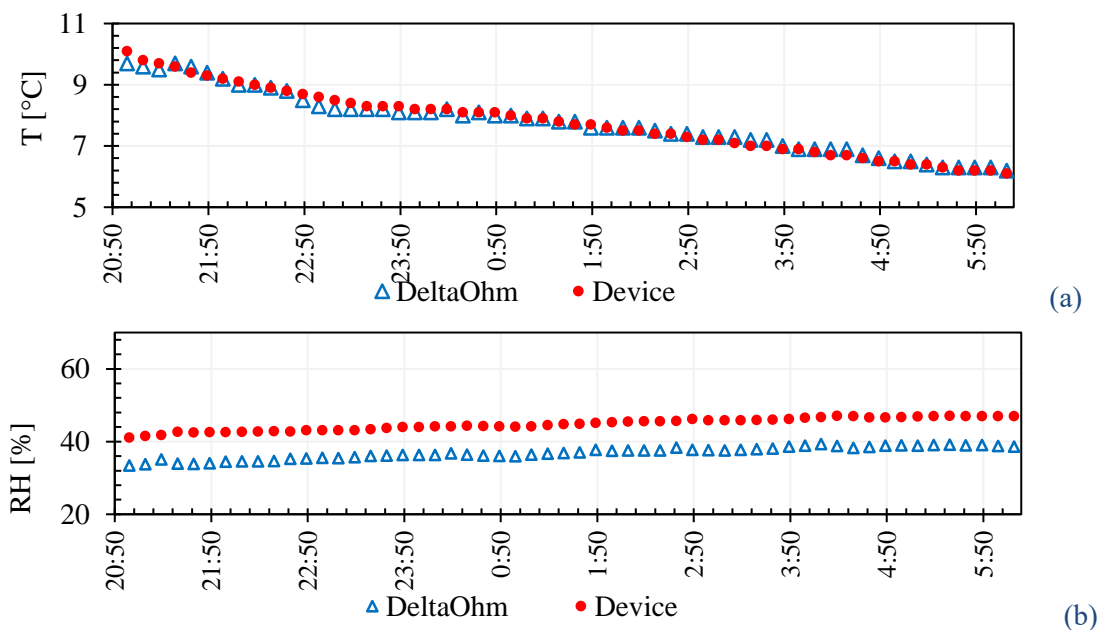


Figure 6. Measurements with the implement device and DeltaOhm HD 32.3: (a) temperature (T) and (b) relative humidity (RH) of an indoor environment.

The measurements for a cold climate were made in Imata inside a dwelling during the month of June, one of the coldest months of the year in this village (see figure 5). Figure 6a shows the temperatures obtained every 10 minutes during 9 hours. The average difference is 0.6 °C, and in figure 6b, the relative humidity measured in the indoor environment shows an average difference of 6%. Although the measurements differ for the devices, the trends are similar.

The calibration curves for the device were determined with 55 points. For temperature and relative humidity, the coefficient of determination R^2 is 0.987 (see figure 6a) and 0.952 (see figure 6b), respectively.

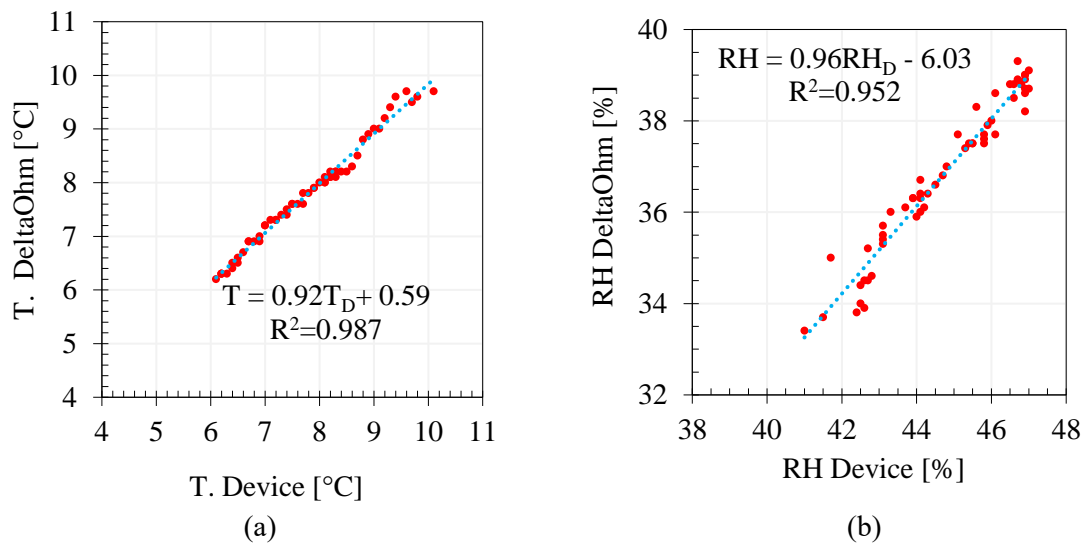


Figure 7. Calibration curve for (a) temperature (T) and (b) relative humidity (RH) sensors.

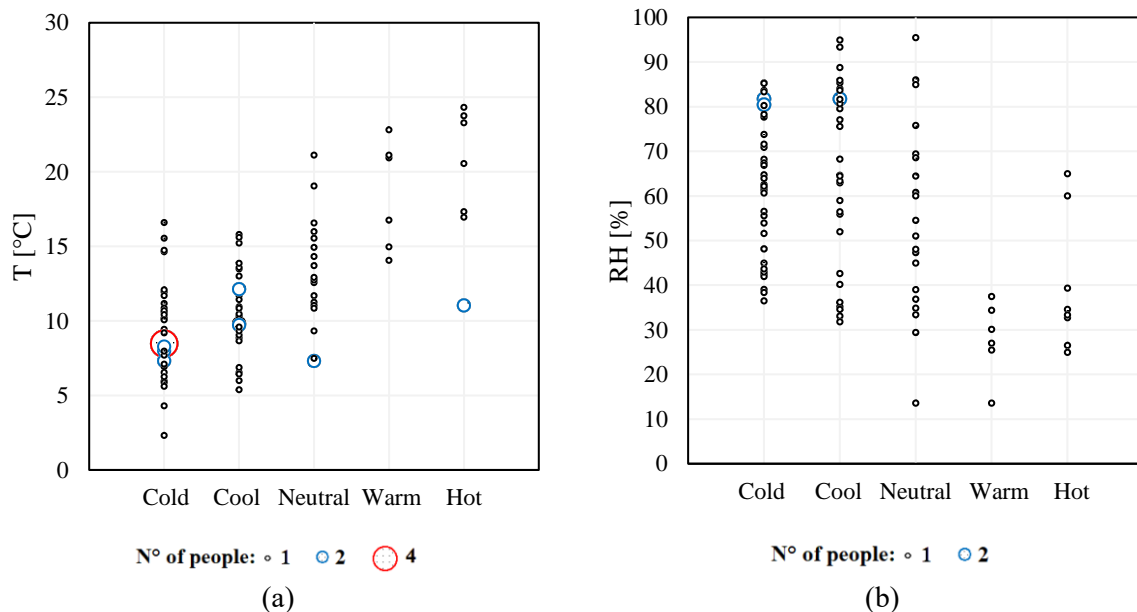


Figure 8. (a) Thermal sensation of participants and indoor temperatures (T) recorded on the device. (b) Thermal sensation of participants and relative humidity (RH) recorded on the device.

3.2. Early results of thermal sensation study

Devices were given to 10 inhabitants of Imata to collect the required information. The results are shown in figures 8 and 9. In figure 8a, the horizontal x-axis corresponds to the thermal sensations of the participants in 5 scales (cold, cool, neutral, warm and hot), and the vertical y-axis corresponds to the temperature of the indoor environment. The records correspond to residents of Imata, which has a cold climate, and the diversity of responses is due to the level of clothing of the participants. For example, when the temperature was approximately 15 °C, the response was "cold", and it is likely that the inhabitant had been wearing very little clothing. The surveyed participants were in a neutral state at approximately 14 °C, with some exceptions. In figure 8b, the vertical y-axis corresponds to the relative humidity of the indoor environment. When the environment was very dry, perceptions of "warm" and "hot" were recorded. In other cases, the high humidity was due to periods of rain in Imata.

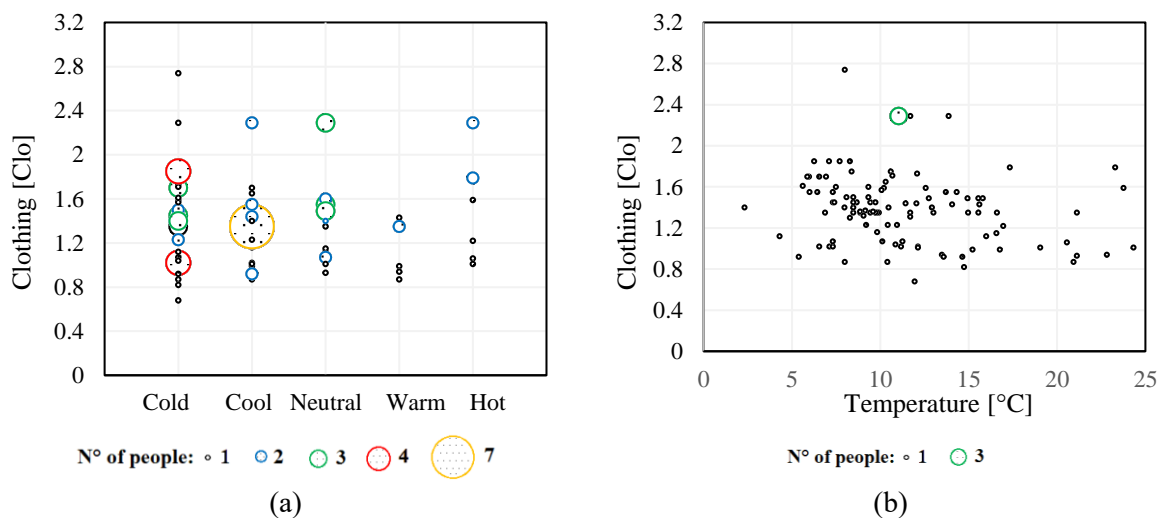


Figure 9. (a) Thermal sensation of people and clothing recorded on the device. (b) Indoor temperatures and clothing recorded on the device.

In figure 9a, the thermal sensation of the person is shown on the horizontal x-axis, and the level of clothing worn by people is shown on the vertical y-axis. Even with a higher level of clothing (2.3 and 2.7 clo), the participants indicated a thermal sensation of "cold" because the temperature of the indoor environment was low. In the case of figure 9b, the temperatures are located on the horizontal x-axis. The level of clothing varies from 0.7 to 2.7 clo.

4. Conclusions

With the implementation of the device, it was possible to measure the parameters of temperature, relative humidity, thermal sensation and clothing worn in indoor environments with a good degree of certainty. All information was recorded simultaneously, and the device was inexpensive and used easily available components.

The simultaneous collection of the parameters and the thermal comfort perceptions of the occupants can be evaluated in a short time, and this will allow the identification of new relationships between the interior environment of a dwelling and its inhabitants in the high Andean areas of Peru.

A challenging point is the precision with which the instrument measures the parameters of temperature and relative humidity. The calibration curves show coefficients of determination R^2 that oscillate between 0.95 and 0.98. Thus, useful information can be obtained to model the relationships between the perceptions of the occupants and the environmental parameters.

Working in high Andean areas that are characterised by extreme cold, it is difficult to establish the correct functioning of measurement sensors. Therefore, a challenge is to adapt the implemented device to these conditions while maintaining a low cost.

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