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Technology Report

An Arduino-Based Talking Calorimeter for Inclusive Lab Activities

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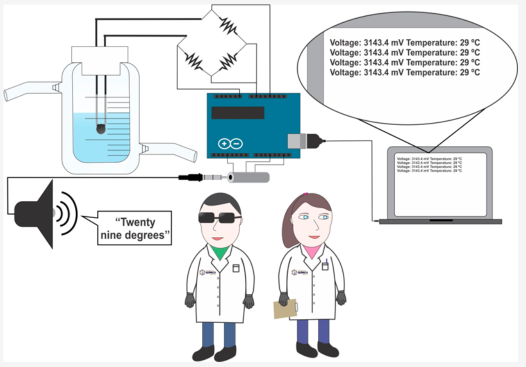
ABSTRACT: This work describes a simple talking calorimeter for the visually impaired based on the Arduino Uno without any shield. An electronic interface was designed using a Wheatstone bridge, a thermistor, or an operational amplifier (opamp). The temperature values are communicated by a loudspeaker connected to pulse-width modulation (PWM) digital output pins 3 and 11 of the Arduino Uno. The system is based on the Talkie library for Arduino Uno. This library was developed using Linear Predictive Coding and includes about 1000 English words. Two new Talkie libraries were constructed, one for Portuguese and another for German. This device can be easily implemented in any teaching laboratory with extremely reduced costs.



KEYWORDS: *General Public, Physical Chemistry, Demonstrations, Hands-On Learning/Manipulatives, Multimedia-Based Learning, Thermodynamics*

In 1994, Spain organized the first World Conference on Special Education that proposed to include all children in regular schools, independent of their physical, intellectual, emotional, social, and linguistic conditions.[1] Blindness and vision impairment are public health problems not fixable by the usual means, affecting 3.8% of world population.[2,3] The main causes are cataract, glaucoma, diabetic retinopathy, uncorrected refractive errors, contagious bacterial infection, and childhood blindness.[3]

Vision is the most important sense for a chemistry student, since laboratory activities are mostly based on visual observations, and the communication of chemical concepts related to the molecular structure, reaction mechanisms, or spectroscopy relies on graphical representations. Hence, it is difficult to include blind and visually impaired (BVI) students in laboratory classes. Although BVI students can be accommodated with the help of non-BVI colleagues, new technology must be developed to enable their independent work in the lab, just like it has become generally possible for the processing of text, sound, and numeric information.

Currently, there has been intense research to overcome such limitations. Teaching strategies were put forward to assist BVI students in taking notes and acquiring figures, drawings, graphs and diagrams, and to assist instructors in communicating mathematical and chemical equations on chalkboard.[4]. Chemoinformatics and other information technologies (IT) strategies were also developed for BVI students to process and produce chemical information.[5] Furthermore, accessibility tools were reported that make it possible for BVI students to perform chemistry laboratory experiments without assistance.[6−8] These tools are based on combinations of software and hardware for teaching chemistry or physics in the laboratory.[6] Supalo et al. developed a handheld device, where light intensity is converted into an audible tone. This device has been designated by the acronym SALS (submersible audible light sensor) and allowed observation of reactions in solution using standard laboratory glassware. The gadget outputs a real-time audio signal when a color changes or a precipitate forms due to chemical transformation.[7] Assistive technology for chemistry lab work was implemented in commercial products,[8] but their cost often hinders adoption by many academic institutions, in which the number of BVI students enrolled in chemistry courses is still very reduced. This is particularly evident in developing countries and underfunded universities.

Therefore, low-cost solutions are needed. Recently, Costa and Fernandes developed an inexpensive pH device for BVI students based on sound frequencies. One additional advantage of this system is that sound frequencies obey a logarithm scale similar to that of pH. On the other hand, accurate measurements require individual training, which is not

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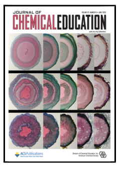

an easy process.[9] Related works included the encoding of infrared spectra based on the correlation between the absorption band intensity and the frequency range of musical instruments,[10] and a simple electronic circuit for generating audio signals.[11] Nevertheless, these proposals are exclusively based on sounds not on speech signals.

Thermochemistry experiments are a common practical in teaching laboratories of chemistry. Recently, Soong et al. reported a multipurpose device with accessibility for BVI students which can be employed as a calorimeter.[12] However, the researchers used an Arduino-compatible TTS module (Emic2) for text-to-speech, with the total cost of this device between \$200 and \$300,[12] which is still high for countries with low financial resources.

In the 1980s, Texas Instruments developed the first speech synthesizers. TMS52xx was used in devices for simulating speech such as Acorn Computer, Apple II Echo 2, and BBC Micro.[13,14] This chip was based on a mathematical model called Linear Predict Coding (LPC).[15] LPC gives a compressed representation of the spectral envelope of the speech signal. It assumes that the signal can be predicted by a linear combination of previous samples (p) according to the following expression:[16]

$$x_n = \sum_{k=1}^{p} a_k x_{n-k} + e_n \quad (1)$$

where a_k represents the linear prediction coefficients and e_n is the error at time n. Equation 1 matches to a source−filter model, where the source function (μ_n) is[16]

$$\mu_n = Ge_n \quad (2)$$

For constant gain (G), the filter is called all-pole with transfer function, $H(z)$, described by[16]

$$H(z) = \frac{G}{1 - \sum_{k=1}^{p} a_k z^{-k}} \quad (3)$$

For short intervals, it is feasible to obtain an optimal estimate of the a_k by minimizing the sum of the squared error.[16] The idea is similar to the least-squares based on a simple linear regression method, where the model's parameters are predicted to minimize the sum of the squared error.[17]

Hence, to digitally simulate the human voice, the TMS5220 chip divides the speech waveforms into 25 ms frames. Studies showed that for an adequate scrambling of the coded bits, a block length of 64 samples is ideal for a 24 kb s^{-1} speech code.[18] TMS5220 has been designed for a 15 kb s^{-1} sampling rate; therefore, it requires 40 samples per second, i.e., a sampling frequency 40 Hz, which consists of frames of 25 ms (1/40). Three speech code parameters, frequency, energy, and reflection coefficients, are employed by the speech synthesizer to remake the sound wave signal. The energy parameter indicates the sound wave's intensity (the gain, G, in eq 3) in the frame. The reflection coefficients (a_k) may vary from 1 to 10, being used to define the digital lattice filter which simulates the vocal tract.[14]

In 2011, Knight and Joachimsmeyer developed a code and libraries in Arduino C^{++} that emulate the TMS5220 chip. This allows Arduino to produce voices without any use of shields.[19] Reports are available regarding the implementation of talking thermometers in the Arduino platform incorporating additional shields.[20]

In this work, we developed a talking calorimeter that uses the Talkie library. This calorimeter enables BVI students to engage in accessible experiments with endothermic and exothermic processes measuring temperature variation in real time and calculating the reaction enthalpy.

■ EXPERIMENTAL SETUP

We constructed two temperature acquisition circuits based on open source electronics platforms, one simple and another a little more complex. These two electronic circuits are presented in Figure S1. In both cases, the hardware consisted of an Arduino Uno,[21] resistors, and one NTC thermistor (Negative Temperature Coefficient B57541G1 series) from EPCOS/TDK.[22] For the first circuit, we mounted a Wheatstone bridge with 3 resistors of 1 kΩ and 1 thermistor of 10 kΩ. The output voltage from the Wheatstone bridge was plugged to the A0-pin of the Arduino Uno analog/digital input.[23] A female audio jack was connected to pins 3 and 11 of the Arduino Uno digital output of PWM, where a headset or loudspeaker was attached (Figure S1A).[24] We connected an amplification circuit before Arduino Uno for the second assembly. The amplification circuit was mounted using the LMC6041 operational amplifier (opamp).[25] The circuit employs LMC6041 in a noninverting configuration with a reference circuit connected to the inverting input and the opamp output.[26] The thermistor was attached to a 10 kΩ resistor to form a voltage-divider that was connected to the noninverting input (3-pin) of the LMC6041.[26] The output of the opamp (6-pin) was connected to the A0-pin of the Arduino Uno. A loudspeaker was attached to the circuit as previously described. The thermistor circuits, Wheatstone bridge, and voltage-divider were powered with +3.3 V. Reference voltage and LMC6041 opamp of the temperature sensing circuit were fed with +1.6 and +5.0 V, respectively (Figure S1B). All voltages were supplied by Arduino Uno. Loudspeaker, Arduino Uno, and amplifier circuit were all connected at the same ground.

Software written in the C language was embedded to the Atmega328 microcontroller from Arduino Uno.[21,23] In order to have the calorimeter communicating the temperature values as speech, the code included the Talkie v1.0.2 library provided in General Public License v3.0.[19] This library contains 1000 words of speech data in English.[19] Some English words were added for this library to complete the vocabulary as required by the talking calorimeter. We also created two new libraries to have the calorimeter emitting Portuguese and German speech signals. The talking calorimeter code and the Portuguese and German libraries are available in the Supporting Information.

A demonstration of the talking calorimeter is presented with endothermic and exothermic processes. The dissolution of potassium chloride in water was employed as an endothermic process, while an exothermic process was studied using a neutralization reaction between hydrochloric acid (500 μL of 4.772 mol L^{-1}, d = 1.029 g mL^{-1}) and sodium hydroxide solution (49.50 mL of 0.3432 mol L^{-1}, d = 1.078 g mL^{-1}). All measurements were done using a jacketed beaker at a constant temperature of 25.0 °C maintained by a thermostatic bath based on previous work.[27] Additional details can be obtained in the Supporting Information.

We tested the talking calorimeter with seven students, four blind and three visually impaired, to receive feedback about the device and suggestions to improve it. For these students, the enthalpimetric processes were presented in the qualitative

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mode for its identification, using vinegar, commercial caustic soda, and potassium chloride.

The experiments with human participants were approved by the ethics committee of the State University of Pará under protocol number CAAE 90054318.0.0000.5168 in August 17, 2018. Before the experiments with BVI students, an informed consent (IC) was read and signed by all participants.

■ HAZARDS

To avoid accidents with BVI students in laboratory experiments, we followed some orientations described in previous work.[9] Also, it is important to alert teachers to be particularly careful with BVI students.

Sodium hydroxide, caustic soda, and hydrochloric acid are harmful since they can cause skin burning and eye damage. Vinegar presents a content of only 4−6% in acetic acid; therefore, the risk of this substance to student health is low. However, vinegar is irritating to the eyes and should be handled with care. Potassium chloride is not described in the literature as a dangerous reagent.

■ RESULTS AND DISCUSSION

As mentioned earlier, we built and tested two data acquisition circuits. In the first circuit (Figure S1A), the Wheatstone bridge was unbalanced according to the following equation:[28]

$$V_{out} = V_{in}\left(\frac{T}{R_1 + T} - \frac{R_2}{R_2 + R_3}\right) \tag{4}$$

Considering that V_{in} = 3.3 V, $R_1 = R_2 = R_3$ = 1 kΩ, and T = 10 kΩ, V_{out} presents an initial value of +1.35 V.

In the other circuit (Figure S1B), the voltage-divider was also powered with 3.3 V, where the thermistor was connected in series to the resistor, both 10 kΩ. Therefore, V_{out} in this second circuit has an initial value of +1.65 V. Arduino Uno does not measure negative values of voltage; hence, it is important that the thermistor circuit is unbalanced initially.

The Wheatstone bridge circuit to measure temperature values presents limitations. For producing a meaningful temperature change due to an enthalpimetric process, a large amount of reagent is necessary. Hence, to minimize reagent consumption, we set up an amplifier circuit using an LMC6041 opamp. This opamp has a high impedance input (ultralow input current),[25] which is ideal for instrumentation devices.[9,25] The LMC6041 operates with a supply voltage, positive or negative, between 4.5 and 15.5 V.[25] We supplied a voltage of +5.0 V through Arduino Uno (Supporting Information), so no external power supply was required. LMC6041 presents a typical slew rate of 0.02 V μs^{-1}; thus, this opamp produces a rapid response due to resistance changes from the thermistor.[25]

The gain of the amplifier circuit is obtained through resistors of the noninverting configuration loop:[26]

$$G = \frac{R_2 + R_3}{R_2} \tag{5}$$

So as R_2 = 1 kΩ and R_3 = 11 kΩ, the G = 12. Therefore, small resistance changes of the thermistor are easily measured by this circuit, reducing the reagent consumption.

Both circuits operate due to the variation of heat in the solution that is detected by the change in resistance of the thermistor. Once the thermistor resistance varies with temperature, we calibrated the circuits to convert voltage to temperature. In the circuits with the thermistor on the Wheatstone bridge and as a voltage-divider, the relationships between output voltage and temperature are given by the respective expressions:

$$T = 1.38 \times 10^3 - 1.39V + 5.03 \times 10^{-4}V^2 - 6.28 \times 10^{-8}V^3 \tag{6}$$

$$T = 35.557253 - 3.3084 \times 10^{-3}V \tag{7}$$

Here, T is temperature in degrees Celsius (°C), and V is voltage in mV.

The Wheatstone bridge circuit works from 5 to 70 °C, and the other works between 22 and 32 °C. We tested the circuit with amplification to measure some enthalpimetric processes in solution. The results are presented in Table 1. In a comparison of the obtained data with that described in the literature, the proposed talking calorimeter was reasonably accurate and precise, and it can be used in classroom experiments with good efficiency.

Table 1. Dissolution and Neutralization Enthalpies Using Temperature Measurement through the Amplification Circuit with the Thermistor Connected to a Voltage-Divider

		Enthalpy, kJ mol^{-1} at 25.0 °C	
Compound	Enthalpimetric Process	Talking Calorimeter	Literature
Potassium chloride	Dissolution in water	+(18.3 ± 0.6[a])	+17.51[29]
Hydrochloric acid	Neutralization	−(60 ± 2[a])	−57.13[30]

[a]Average of three determinations and standard deviation estimate.

The software embedded in Arduino converts the temperature values into speech through the PWM output using the Talkie library.[19] During the user test, temperature readings could be viewed by a supervisor using the serial monitor in the Integrated Development Environment (IDE, open source Arduino software)[21] at the same time that the participant listens to them.

In this test, all participants correctly reported the temperature changes that were emitted by the talking calorimeter. These are very positive results, but our main concern is the participants' feedback about the talking calorimeter. About 85% of the participants described the talking calorimeter as a useful device, but many claimed that the continuous speech signal with temperature readings was confusing.

Initially, the temperature values were spoken every 5 s. According to the BVI participants, this is too much audible information, which can cause stress and loss of concentration. On the basis of this feedback, we improved the software to emit only initial and final temperature values due to the temperature change during the thermal process. For best results, it is important to adjust the "ReferencePrecision" constant through experimental tests (see software code in Supporting Information). This update helps students to calculate the enthalpy of the process and easily decide if the process is endothermic or exothermic; in addition, it reduces the environment's noise.

Between the two circuits tested, the one based on a Wheatstone bridge is simpler to assemble for teachers with little knowledge of electronics, but for accurate quantitative measurements, it is better to assemble the amplification circuit with the thermistor connected to a voltage-divider.

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The sound quality of the of the Arduino's TTS using Talkie library is similar to that heard on the analog phone (8 MHz sample rate, 16 bit of information, mono flavor and 15 kb s^{-1} bitrate). The words are clearly audible, but in some cases a noise can be heard. Nevertheless, it is possible to improve this quality developing a new library based on another speech chip. However, it is important to remember that higher sound quality implies the necessity of more memory space from Arduino.

CONCLUSION

Here we propose an affordable talking calorimeter ($43) that does not use shields. Any teacher, without electronics knowledge, can easily mount it. It can be used in inclusive chemistry lab activities with BVI and non-BVI students. The new device can be easily customized and can be connected to headphones for the simultaneous operation of several users in the same lab with no interference between them.

At its current version, the talking calorimeter can emit English, Portuguese, and German speech signals (Supporting Information), but it is not limited to these languages. Using the Matlab's toolbox for LPC or QboxPro,[31] an ancient software for Windows 95 developed by Quadravox that converts a wave format file (8000 kHz, 16-bit-mono) to LPC, it is possible to construct a vocabulary for any language.

Text-to-speech is a potential market; therefore, an increase in the research in this area of study is expected in the coming years.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available at https://pubs.acs.org/doi/10.1021/acs.jchemed.0c00148.

Additional files providing greater detail on electronic circuits, embedded software, libraries for Portuguese and German, and the experimental setup (PDF, DOCX)

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Notes

The authors declare no competing financial interest.

A video demonstration is available at https://youtu.be/mghwYriI5fU.

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