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Teaching labs for blind students: equipment to measure the thermal expansion coefficient of a metal

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Abstract
We design a Physics Teaching Laboratory experience for blind students, to measure the linear thermal expansion coefficient of an object. We use an open-source electronic prototyping platform to create an interactive electronic device that converts visual signals into acoustic signals, allowing a blind student to participate at the same pace with his/her classmates during the laboratory session. This adaptation was tested with a student group where one of them was blind, turning out to be a highly rewarding experience for the latter, as it was the first time he was able to fully participate in a laboratory session.

Supplementary material for this article is available online

Keywords: physics education, inclusion, thermal expansion

(Some figures may appear in colour only in the online journal)

1. Introduction

Measuring the coefficient of thermal expansion of an object is a typical laboratory experience in an introductory thermodynamics course for science and engineering students.

In our experimental setup, the students must determine the change in length of a straight aluminium tube as a function of temperature, at constant atmospheric pressure. The thermal expansion of an object of length L can be specified by the relationship between the fractional change in length $\Delta L/L$ and the temperature variation ΔT. This relation is characterised by the linear expansion coefficient α, which depends on the material (aluminium, in our case) but not on the size of the object [1, 2]:

$$\frac{\Delta L}{L_0} = \alpha\ \Delta T. \tag{1}$$

Here L_0 corresponds to the natural length of the tube at room temperature. In our current laboratory sessions, for a blind student it is impossible to do the actual measurements because the instrument readings are usually of visual character. Therefore, a change in the measuring devices are necessary in order to include this student in the lab experience [3, 4]. A natural alternative to visual readings is to include sounds that relate to the value of the physical variable they intend to measure. An open-source electronic prototyping platform (Arduino board) offers the possibility to use a variety of sensors and electronic components that can be used to improve the data acquisition and control of different experiments in physics [5–13].

In general, curricular adaptations for blind students have always been a great challenge [14–19]. Many schools struggle to provide the equal access that must be given for homework material, classes and software for these students [20–22]. Consequently, making correct protocols to work with visually impaired students in physics laboratories is today a necessity.

In this work, we present the successful case of adaptation of a teaching laboratory session (in this case aimed at the measurement of the thermal expansion coefficient for aluminium) for a blind student in an undergraduate physics course.

Our intervention consisted in modifying the instruments used for the length measurement of a metal rod. The readings of this equipment are usually done visually. We devised a conversion to audible signals, with an accuracy comparable to the resolution of the original instrument.

The student, who was visually impaired from a very young age, was attending his second year in computer engineering and had passed his first two courses 'Introduction to Physics' and 'Mechanics', where appropriate modifications were done in the lectures for him to complete the courses. Among the modifications were the use of tactile graphics (such as in [3]) and the use of the 'Accessibility' option in Microsoft Word™ that translates the text into sounds. The student also showed excellent handling with Microsoft Excel™ software.

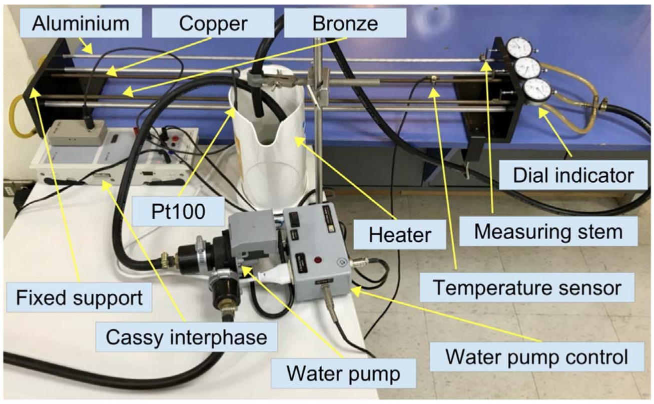
In section 2 we describe the laboratory experiment with the regular instrumentation and our modification for visually impaired students. In section 3 we show the results and performance of the experiment operated by the student. In section 4 we state our conclusions.

2. Experimental setup

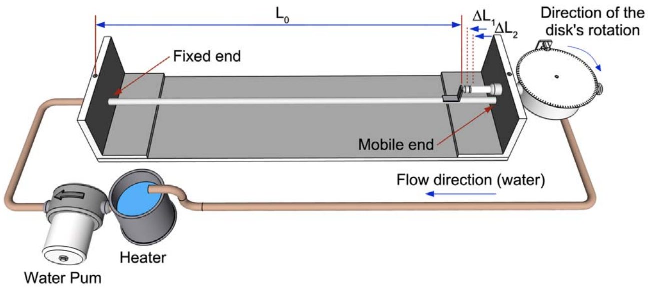
2.1. The regular setup

In this lab experience, we built a water circulating system (see figure 1) composed of a water pump, an electric kettle to gradually heat up the water, and hoses connected to the metal tubes whose respective lengths have to be measured as a function of temperature. The temperature of the water can be selected in the computer connected to the interface. This setting activates a kettle with a temperature control system that uses a Pt100 temperature sensor for feedback. However this is not the temperature datum used in the determination of the thermal expansion coefficient: for better precision, the temperature of the metal tubes is measured directly by a solid-state sensor attached to the copper tube, as explained below.

There are three tubes of different materials (aluminium, copper, and bronze), of 0.8 mm in diameter. The tubes are located on an insulating plastic base with one end fixed and the other free to allow for their thermal expansion. The temperature of the tubes is measured with



(a)



(b)

Figure 1. (a) Picture of the standard system for measuring the thermal expansion of metal tubes. The main parts are indicated: the three tubes to be measured are arranged top to bottom: aluminium, copper and bronze; the dial indicators provide a visual reading of the length of each tube; a water heater with a Pt100 sensor for the water temperature control; the location of the tube temperature sensor; the water pump; and the Cassy interface. (b) Simplified drawing of the dilation measurement apparatus. The metal bar is fixed on the left end and free to slide on the right end, where the dial indicator is attached. The dial indicator mechanically transforms the linear displacement into a rotation of the axle.

a solid-state LM35 sensor attached to the copper tube (see figure 1), as the three tubes are assumed to be at the same temperature, for simplicity of the setup. This is a good approximation given the expected precision of the experiment.

The standard values for the thermal expansion coefficients of the materials under study are [23]:

$$
\begin{aligned}
\alpha_{\mathrm{Al}} &= (21\ -\ 24) \times 10^{-6}\ 1/^\circ\mathrm{C}, \\
\alpha_{\mathrm{Cu}} &= (16.0\ -\ 16.7) \times 10^{-6}\ 1/^\circ\mathrm{C}, \\
\alpha_{\mathrm{Brz}} &= (17.5\ -\ 18.0) \times 10^{-6}\ 1/^\circ\mathrm{C}.
\end{aligned}
$$

These standard values show a rather wide range, because they depend on the specific microstructure of the material, which in turn depend on the fabrication process. Therefore, in previous tests we have verified that the thermal expansion coefficients of the tubes in our lab are within the range the standard values. Our reference results are

$$\begin{aligned}\alpha_{\mathrm{Al}} &= 24.0 \times 10^{-6}\ 1/°\mathrm{C},\\ \alpha_{\mathrm{Cu}} &= 16.6 \times 10^{-6}\ 1/°\mathrm{C},\\ \alpha_{\mathrm{Brz}} &= 18.0 \times 10^{-6}\ 1/°\mathrm{C},\end{aligned} \tag{2}$$

within an estimated error of about 1%.

Almost all steps in this lab experience can be performed today by a student with impaired vision thanks to today's accessibility software, except for the reading of the dial indicators (see figure 1). Therefore, for this reading we have designed special instrumentation that we present here, which is the main subject of this article. The dial indicator is an enclosed instrument so that neither the needle nor the scale behind it are accessible to touch.

Our purpose is to include a student with impaired vision together with his/her classmates in the measurement process within the regular laboratory session. This laboratory experience is usually done in groups of two or three students.

In this adapted lab session, we expect the blind student to do all the measurements that are necessary to obtain the thermal coefficient of the aluminium tube (i.e. α_{Al}).

In the next subsection, we describe the modifications that were done to carry out this experience, replacing the visual measurement of the dial indicator by an audible type, using an Arduino platform.

2.2. Our modified setup

Our modification consists in replacing the dial indicator with a disk of 2.8 mm inner radius and 40 mm outer radius and 3 mm thick, with 100 equally spaced slits 1 mm × 4 mm on the outer edge (see figure 2). The turn of the disk between consecutive slits corresponds to a 0.01 mm dilatation of the tube. The disk is made of black non-translucent acrylic with a mass of 13.3 g. A point to be considered in this design is that the disk should be large enough to have good resolution with reasonably cheap optical devices (miniature devices are more expensive) and yet it should be small and light enough to have a low inertia for the mechanical parts.

The reading of the slits is done with a photogate sensor (model FC-03) generally used in small motor speed controls. The photogate sensor has a gap of 5 mm where the 3 mm thick disk can fit through (see figure 3(a)). The original dial indicator is replaced by the acrylic disk. This is done by removing the dial indicator from its axis, and mounting the disk in its place (see figure 2).

The photogate sensor feeds into an *Arduino nano board*, which is programmed to count the number of slits passing through the sensor when the disk rotates as a result of the tube expansion. The Arduino sends a signal to a speaker that emits an audible beep per every count. In addition, the Arduino stores the number of counts and, because it also stores the calibration of millimetres versus counts, it can vocalise the corresponding millimetres of dilatation. This vocalisation is done utilising a *Talkie Library* software, an Arduino library developed by Peter Knight and Armin Joachimsmeyer, which consists of a software implementation of the Texas Instruments speech synthesis architecture from the late 1970s early 1980s. This vocalisation is emitted when the S1 button is pressed (see figure 3(b)).

Here the vocalisation was only used as a double verification of the measurement, because the student usually uses the beeps as measurements. The synthetic voice is a help in case external noises impede the correct hearing of the beeps. If one needs to repeat the measurement, button S_2 (see figure 3(b)) resets all stored numerical values, emitting two sound pulses. Additionally, a light-emitting diode flashes every time a beep is emitted, for the teacher to verify the measurement.

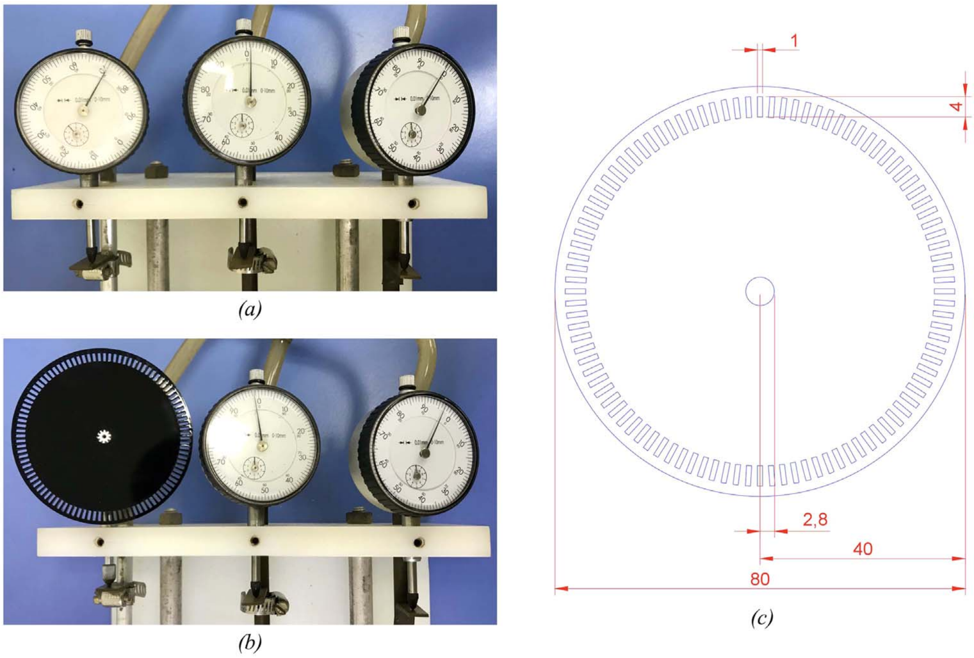


Figure 2. (a) Regular dial indicators that measure the thermal expansion of the bronze, copper and aluminium tubes (from left to right, respectively). The long pointer has a resolution of 0.01 mm and the short pointer 1 mm. (b) View of the modified indicator with the black disk mounted on its axis; its angular position can be measured with a photogate. (c) Diagram of the modified dial indicator; the numerical values shown are in mm; every step between slits corresponds to 0.01 mm in length expansion; one full turn has 100 slits, corresponding to 1 mm in length expansion.

The Arduino programming code implemented for this experience can be found in the supplementary material, available online at stacks.iop.org/EJP/41/035704/mmedia.

3. Results and discussion

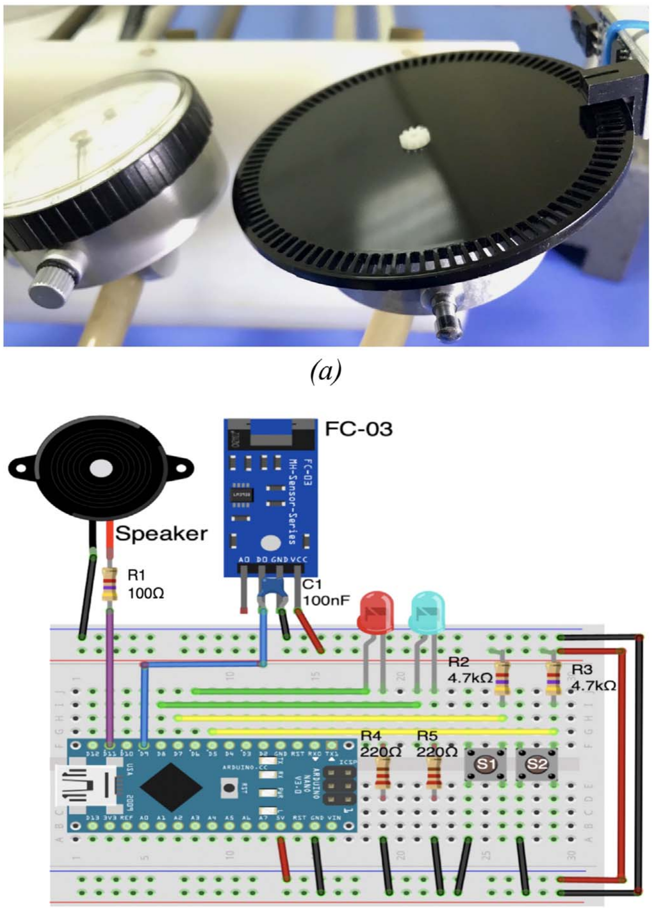
In table 1 we show the data for the thermal expansion of the aluminium tube, obtained by the blind student, while the temperature values T were read by his partner (a student with normal vision).

Once the blind student finished collecting the data, he performed a linear regression where the slope indicates the value of the coefficient of linear expansion:

$$\alpha_{\mathrm{Al}}^{\mathrm{exp}} \sim 22.86 \times 10^{-6}\,\frac{1}{^{\circ}\mathrm{C}}. \tag{3}$$

The reference value for the aluminium given by equation (2) and the linear regression done by the student is shown in figure 4.

This result is clearly within the expected range according to equation (2).To validate his result, we collected the results from other 29 group reports (58 students), selected among those with the best grades of their respective classes (our 'high-performance' groups). The data are presented in figure 5. The average value of the slope for all linear regressions made by these other groups is



(a)

(b)

Figure 3. (a) Photogate FC-03 mounted with the modified disk made of black non-translucent acrylic. (b) The circuit with the Arduino Nano v3.0 board, the speaker, the photogate FC-03, the LEDs and the USB connector to the computer.

$$\langle \alpha_{\mathrm{Al}}^{\mathrm{HP}} \rangle \sim 23.89 \times 10^{-6} \, \frac{1}{^{\circ}\mathrm{C}}, \tag{4}$$

which is also within the range of expected values given by equation (2). The standard deviation of this set of values is

$$\Delta \alpha_{\mathrm{Al}}^{\mathrm{HP}} = 4.81 \times 10^{-6} \, \frac{1}{^{\circ}\mathrm{C}}, \tag{5}$$

clearly showing that the value obtained by the blind student is well within the range of the measurements performed by the other students.

Nevertheless, we must point out one particular source of systematic errors of our experimental setup: the segmented disk allows for tube dilatation measurements in multiples of 0.01 mm only. This source of error can be improved by using a smaller size photogate (which are more expensive) or by enlarging the segmented disk; however the latter should not

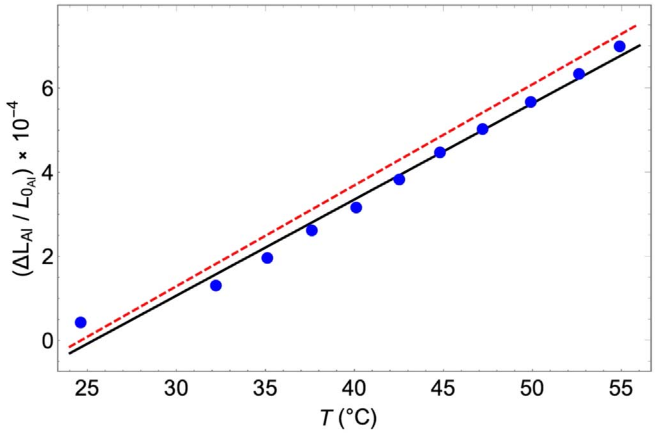


Figure 4. Data points from table 1 for the determination of the thermal expansion coefficient of the aluminium tube. The solid line corresponds to the linear regression of the data and the dashed red line depicts the reference curve obtained with the listed value for aluminium shown in equation (2). The slope of the line corresponds to the thermal expansion coefficient α.

Table 1. Measurements of the length expansion, ΔL, as a function of temperature, T, of an aluminium tube of room temperature length $L_0 = 0.915$ m. The length data were taken by the student with impaired vision and the temperature readings were registered by his laboratory partner.

Measurements taken by the student with impaired vision			
Measurement number (n)	T (°C)	ΔL (10^{-4} m)	$(\Delta L/ L_0) \times 10^{-4}$
1	24.60	0.40	0.44
2	32.20	1.20	1.31
3	35.10	1.80	1.97
4	37.60	2.40	2.62
5	40.10	2.90	3.17
6	42.50	3.50	3.83
7	44.80	4.10	4.48
8	47.20	4.60	5.03
9	49.90	5.20	5.68
10	52.60	5.80	6.34
11	54.90	6.40	7.00

be pushed too far, as we already explained, because a larger disk implies a larger moment of inertia, which causes mechanical oscillations.

4. Conclusions

We devised an adaptation for blind students of a teaching laboratory experience dedicated to measure the thermal expansion coefficient of a metal tube. The purpose of our adaptation is to allow a blind student to fully participate in the measuring process, in addition to his/her usual participation in the data analysis and report. Our adaptation consisted in modifying a length

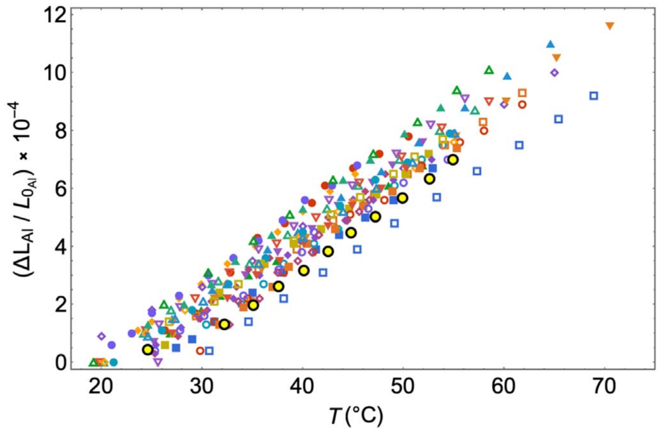


Figure 5. Data points of 29 reference student groups. The slope average is $\alpha_{Al} \sim 23.89 \times 10^{-6}$ [1/°C]. Yellow circles with black borders represent the data obtained by the visually impaired student.

gauge usually in the shape of a dial, by connecting a segmented disk with a photogate sensor in replacement of the needle attached to the axis of the dial. In this way, the sensor reads the angle of rotation of the disk, which is proportional to the dilatation of the material (in this case, an aluminium tube). The reading of the photogate sensor feeds into an Arduino platform which is programmed to count the number of slits passing through the photogate sensor and to send signals to a speaker, converting in this way, a visual signal into one of the audible type.

We tested the device in a real laboratory session with a student who was blind from very young age. We found that the student was able to do the measurements with ease and his results were comparable to those of other student groups that had completed the experience successfully. At the end of the experiment, the student approached us to express that he felt much satisfaction by being actively integrated in the measurement process, in addition to his usual duties he was involved in other experiences such as doing the analysis of data and writing the reports.

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