Journal of Physics: Conference Series

PAPER • OPEN ACCESS

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To cite this article: Lars-Jochen Thoms *et al* 2019 *J. Phys.: Conf. Ser.* **1223** 012007

IOP Conf. Series: Journal of Physics: Conf. Series **1223** (2019) 012007 doi:10.1088/1742-6596/1223/1/012007

Real-life physics: phonocardiography, electrocardiography, and audiometry with a smartphone

Lars-Jochen Thoms, Giuseppe Collichia and Raimund Girwidz

Chair of Physics Education, Faculty of Physics, Ludwig-Maximilians-Universität München, Theresienstr. 37, 80333 München, Germany

E-mail: l.thoms@lmu.de

Abstract. To foster student motivation and engagement, we combined authentic contexts, procedures, and materials by assessing biomedical physics topics with a smartphone. Selected experiments with simple aids allow for the examination of a student's heartbeat in various ways: e.g., phonocardiography and electrocardiography. In addition, students can test their frequency-dependent hearing threshold. These contexts lead to an understanding of various physics concepts in a meaningful way.

1. Introduction

Student engagement in learning processes plays a crucial role in facilitating intellectual development. Especially in high schools, educators should choose teaching strategies that foster student engagement. Herrington and Oliver reviewed literature on situated learning and identified nine basic elements that led to the nine steps of the *Instructional Design Framework for Authentic Learning Environments* [1]. The first two steps refer to authentic contexts that reflect the way the knowledge will be used in real life and authentic activities. Situated learning should make use of authentic contexts by means of anchored instruction in a way that emphasizes the application of the knowledge to be acquired in everyday life. Furthermore, situated learning should allow for the conducting of authentic activities relevant to everyday life.

Recent approaches use authentic objects as learning anchors and starting points of learning paths. Much attention is given to the use of smartphones and tablets in physics education as supplements—or even as substitutes—for conventional experimental materials. On occasion, the possibility is shown that learners can carry out their own measurements of authentic physical data with their own mobile device.

What is more authentic for a student than their own body? Examining organs like the heart or the ears allows for the learning of physics based on a particularly familiar context. To foster student motivation and engagement, we combined authentic contexts, procedures, and materials by assessing biomedical physics topics with a smartphone.

Selected experiments with simple aids allow for the examination of a student's heartbeat in various ways (e.g., phonocardiography [2] and electrocardiography) as well as the frequency-dependent hearing threshold [3].

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These contexts lead to an understanding of various physics concepts in a meaningful way. Furthermore, these experiments allow for discovery-based and inquiry-based learning. Students are able to experience and learn experimental techniques and inquiry strategies in a self-responsible and multidisciplinary way. Since these experiments are conducted with everyday materials and may easily be replicated at home, students can also conduct inquiry-based experiments at their own liberty.

Students can conduct their examinations in the same way that medical staff do. In the case of phonocardiography and hearing tests, they can even use professional software developed for clinical use.

2. Phonocardiography

When a stethoscope is placed on the chest over the heart, sounds coming from the heart can be directly heard. These sound vibrations can be captured through a microphone and the electrical signals from the transducer can be processed and plotted on a phonocardiogram. Students can easily use a microphone and smartphone to capture and analyse characteristic heart sounds.

2.1. Heart sounds

During the cardiac cycle, the heart produces rhythmic sounds. The major components of cardiac sounds are associated with the abrupt acceleration or deceleration of blood in the cardiovascular system [4]. The most fundamental and easily recognized heart sounds are defined as the first heart sound S_1 and the second heart sound S_2 (see figure 1). The first heart sound occurs at the beginning of ventricular contraction in the frequency range of 10–180 Hz with duration: 0.12–0.15 s. The shorter second heart sound arises at the end of the ejection phase of the systole and is related to the closure of the aortic and pulmonary valves; this sound occurs in the frequency range of 50–250 Hz with duration: 0.08–0.12 s [5, 6].

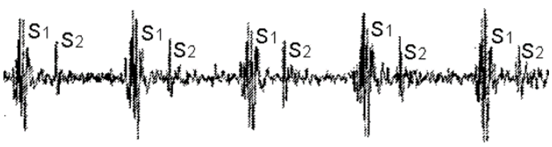

Figure 1. Simplified phonocardiogram of normal heart sound [2].

2.2. Stethoscope acoustics

Common stethoscopes have a dual-head chest piece consisting of a diaphragm and a bell. while the diaphragm transmits higher pitched sounds more efficiently (e.g., lung sounds), the bell is better suited to the transmission of lower-pitched sounds (like heart sounds) [7, 8]. The choice of tube length and internal diameter of a stethoscope involves the balancing of several characteristics: First, the volume of the tubes should be small to ensure large pressure changes. Second, small tube diameters also increase air friction, which reduces the range of pressure modulation.

2.3. Low-cost phonocardiography

A low-cost system for capturing heart sounds consists of a bell, a tube, and a small microphone connected to a smartphone for processing and creating a graphical record (see figure 2).

A more advanced system includes an adapter for headphones and therefore allows for simultaneous listening to the recorded heart sounds (see figure 3a). This makes it easier to find the right position for the bell on the chest. The bell should be held with only low pressure at the area of contact. Otherwise, the stretched skin becomes a diaphragm, dampening low frequencies. The microphone is situated inside the flexible tubing at the end of the acoustic

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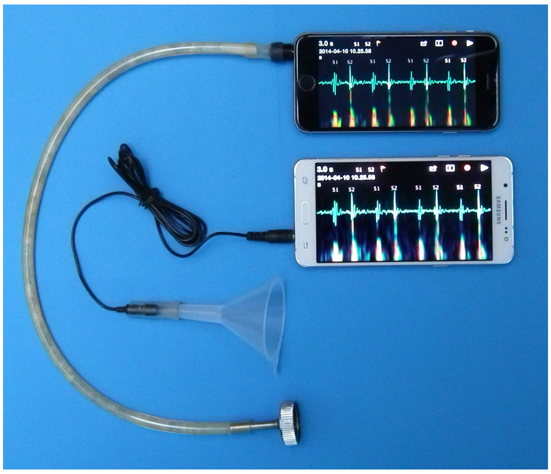

Figure 2. Two detection methods: heart sounds are captured (a) after transmission through the tube or (b) by a microphone that is placed close to the bell. The bell is made (a) from a piece of bicycle inner tube with the valve hole covered by a union nut [2] or (b) simply from a plastic funnel.

Figure 3. (a) Method that allows for simultaneous listening to heart sounds and (b) direct recording.

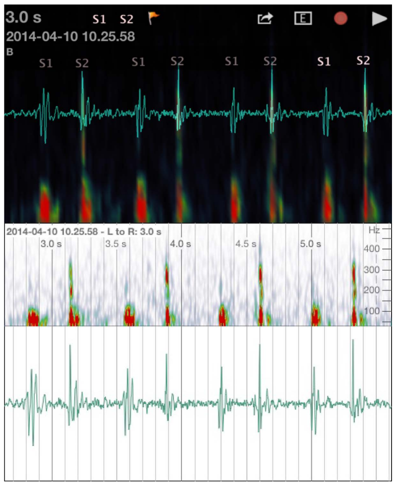

Figure 4. A Phonocardiogram and corresponding spectrogram [2].

pathway, or close to the bell. The microphone should have good response characteristics for low frequency sounds, preferably from as low as 20 Hz upwards. With devices having a sensitive built-in microphone at a suitable position that allows for recording of low frequencies (e.g., with a iPhone 6s) it is even possible to record a phonocardiogram easily by placing the device with the built-in microphone directly on the chest (see figure 3b).

The first and second heart sound appear clearly in the phonocardiogram shown in figure 4. The amplitudes of these sounds depend on the position of the chest piece. The heart rate can be determined and probable arrhythmia can be detected.

3. Electrocardiography

Myocardial contraction is triggered whenever a wave of electrical impulses passes through the heart. The pattern of electrical excitation spreads coordinately over the structure of the heart. This results in a measurable change in potential difference on the surface of the body of the subject. The recording of the resultant signal from specific points on the body is known as an electrocardiogram (ECG). Students can record an ECG with a smartphone using the headset input microphone and a suitable sound app.

3.1. The heart electric dipole
Each cardiac cycle begins with the spontaneous generation of an action potential in special pacemaker cells, which are located in the superior lateral wall of the right atrium. The action potential travels from there at 3-5 m/s to the lower tip of the heart. The propagation of electric potentials establishes a complicated charge and potential distribution that changes in time as different parts of the heart are stimulated. Differences in the concentration of ions between the interior and the exterior of a cell lead to a voltage called the membrane potential. Myocardial cells at rest have a negative membrane potential (more positive exterior charge). Stimulation above a threshold value induces the opening of voltage-gated ion channels and a flood of cations into the cell. The positively charged ions entering the cell cause the depolarization characteristic of an action potential. After a delay, potassium channels reopen, and the resulting flow of cations out of the cell causes repolarization to the resting state.

In a first approximation, the total electric charge of the heart can be modelled as an electric dipole. This heart dipole changes both direction and magnitude during the cardiac cycle, and generates a variable potential on any point of the body [9].

3.2. Recording electrical potentials
If two electrodes are placed on the skin on opposite sides of the heart, electrical potentials generated by the field of the dipole can be recorded (see figure 3a). The electrodes can be placed anywhere on the arms as long as the left and the right electrode have the same distance from the heart. Although the power of the measured signal decreases with increasing distance between the electrodes and the heart, the shape of the signal remains almost unchanged. The intensity of the signal also depends on the amplification of the measuring system and the electrode-skin contact resistance. While the resistance through the human body is relatively low, the electrode-skin contact resistance may vary greatly. Therefore it is important to place the electrodes on wet and thin skin.

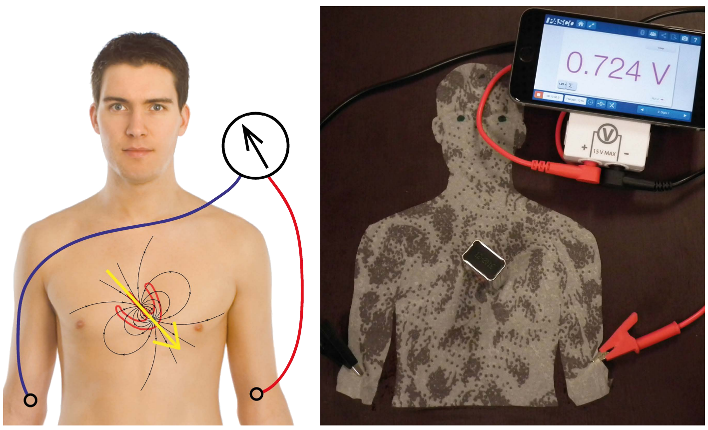

Figure 5. Recording electrical potentials: (a) rotating heart dipole and (b) analogous school experiment.

3.3. Analogous experiment
For a better understanding of how electrical potentials are placed in the human body when a heart electric dipole is generated, a simple experiment should be done. In this experiment, a wetted sheet of absorbing kitchen paper is shaped in the form of upper torso and arms. A 9 V block battery is placed upside down on the wetted sheet at the position of the heart. The two poles of the battery create a dipole between the two points that are connected to the terminals

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of a voltmeter (see figure5b). An ion current and potential field will then be generated. It is easy to measure how the electrical potential varies when the battery is rotated. Because the battery runs out quickly, it is advisable to use rechargeable batteries.

3.4. Smartphone single lead ECG

Several options exist for getting electric signals into the smartphone. One of the most obvious ways to get analog signals into a smartphone is through the headset input when a headset connector with a microphone input is present [10, 11, 12, 13]. One should be aware that:

(i) A bias voltage used to potentially power a microphone is present.
(ii) The headset input expects to see a particular load in order to signal the operating system that an external microphone is present.
(iii) A smartphone may cut off low frequencies, hence, making the recording of a heartbeat less accurate.

In clinical use, 12-lead ECG is a common standard with electrodes placed on both arms, one leg, and on the chest. As a simplified demonstration in class, a single lead ECG can be used by students. Two plates of stainless metal are used as electrodes to build contact with the body (see figure 6). To be sure the smartphone will select the microphone input signal, one must place a suitable resistor (1-10 kΩ) in parallel with the input. The signal processing (amplification and low-pass filter) of the acquired cardiac cycle will be performed directly on the smartphone (see figure 7). Particularly suitable for this is the app *Stethoscope* that was also used in section 2 [14].

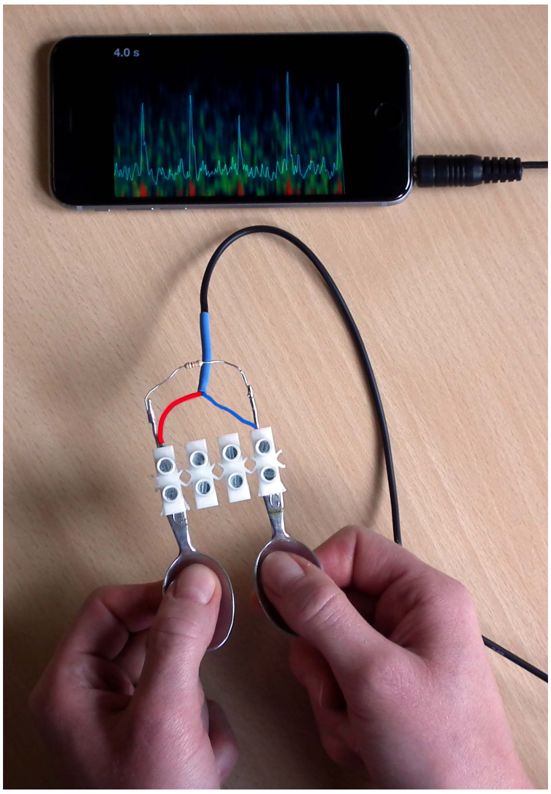

Figure 6. Low-cost experimental ECG setup.

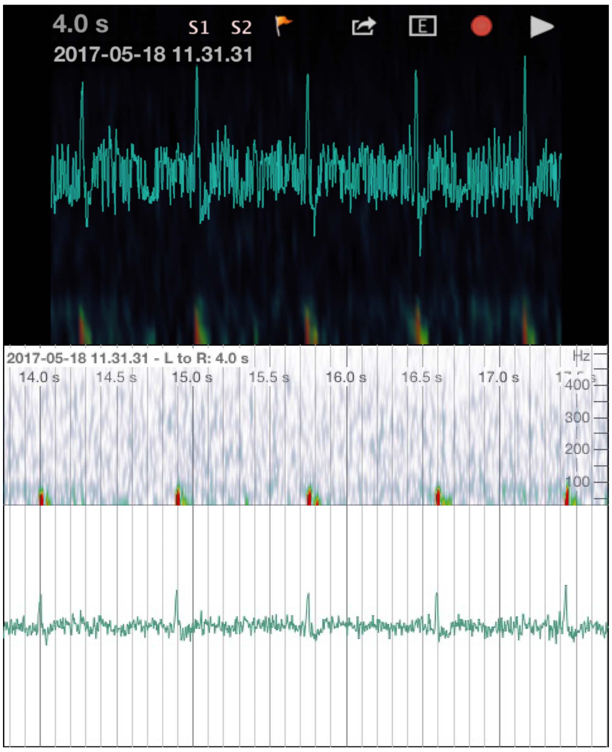

Figure 7. Electrocardiogram (ECG) obtained with an iPhone 6s and the Thinklabs Stethoscope App.

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4. Audiometric test

Audiometric hearing tests present sounds at different levels and different frequencies to a listener. The listener indicates the sounds that he/she is able to perceive in order to determine the lowest level (the threshold of hearing) for each frequency. Students can use a smartphone with specific apps to measure the frequency-dependent hearing threshold of their own ears.

4.1. The ear

The outer ear (pinna) collects sound waves from the environment and funnels them down the ear canal to the eardrum, which begins to vibrate (see figure 8). The vibration of the eardrum is transmitted to the oval window of the inner ear by means of the tiny bones, hammer, anvil, and stirrup. The stirrup delivers vibrations through the membrane of the oval window to the cochlea, which is a spiral tube filled with liquid and lined with microscopic hair cells. Vibrations of the oval window produce waves of compression and rarefaction propagating through the cochlea and subsequently cause the hair cells to move. The movement of hair cells generates nerve signals that our brain then interprets as sound.

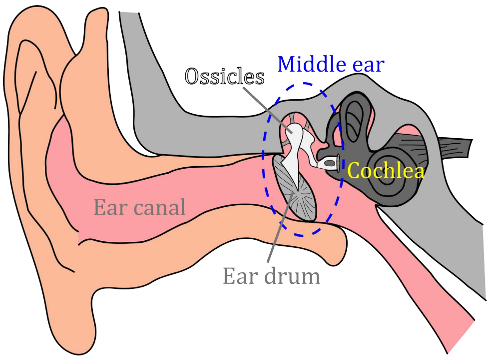

Figure 8. Basic structure of the ear [3].

4.2. Ear's sensitivity

The ear is most sensitive to frequencies in the range of 2-5 kHz with a peak at about 3.7 kHz, resulting from resonance with the ear canal which corresponds to a closed tube length of about 2.5 cm. This high sensitivity region is very important for understanding speech, because frequencies between 500 Hz and 3 kHz are most commonly used during ordinary conversation.

4.3. Smartphone hearing test

When smartphones are sold in a bundle with distinct ear phones (e.g., Apple iPhone 6s together with Apple EarPods) it allows developers to calibrate the measurement process for this specific bundle against a standard audiometric setup [15]. As an alternative, biological calibration for a specific bundle consists of approximating the reference sound level via the hearing threshold of one or more healthy young persons with normal hearing [15, 16]. We carry out the hearing test on a smartphone, and standard earphones which come with the basic version of the Apple iPhone 6s (figure 9).

Several apps for hearing tests are available. E.g., *AudCal* is made for professional use and very well calibrated [15]. The hearing application used in this study, *Hearing Test & Ear Age Test*, is made for self-assessment, easy to use, and available for free [17]. Nevertheless, the program utilizes the same principles as a conventional test. Students can perform a self-test in approximately 5 minutes. Figure 10 shows an example measurement of sound level in dB HL for seven frequencies. The results show slight hearing loss for middle frequencies (250 to 4000 Hz) and mild hearing loss for 8000 Hz.

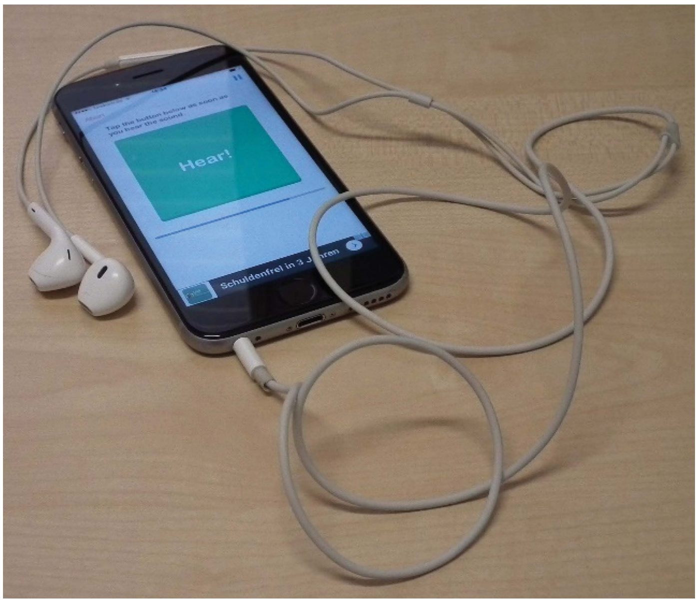

Figure 9. Smartphone and ear phones used in the hearing test.

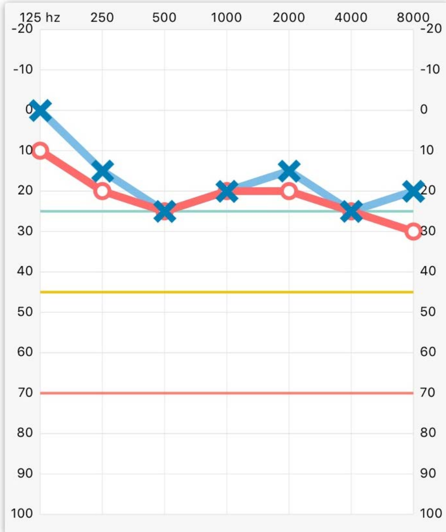

Figure 10. A hearing test result. Left ear (blue crosses) and right ear (red circles).

5. Discussion

5.1. Phonocardiography

In general, several factors complicate sound collection. Varying heart rhythms, background noise, respiratory sounds, and noises produced by shifting the stethoscope head on the skin all contribute to the difficulty in isolating cardiac sounds, which are generally low-intensity signals. For this reason, all efforts should be made to maximize the signal and minimize acoustic and electrical noise. Furthermore, improving and testing different options for stethoscopes promotes greater understanding of acoustics. Noise signals make it difficult for an inexperienced user to distinguish between normal and abnormal cardiac sounds. Nevertheless, the use of new intelligent mobile devices in the field of auscultation is actually a current research topic in several European research projects [18, 19, 20]. A thorough review of state-of-the-art products and smartphone stethoscope apps can be found in the literature [21]. We used and recommend the stethoscope app from Thinklabs available on the Apple App Store for free [14].

5.2. Electrocardiography

The ECG can be an interesting teaching resource for young people because of its reference to an important bodily organ, and because it can be carried out with the use of a smartphone. The physical concepts and theory underlying the ECG can be explored without having in-depth knowledge of the subject. It is therefore suitable for both secondary school students and university students. In general, noise masks the recorded signal, which is of low-intensity. It is important to remark that the smartphone ECG presented here should be used only for teaching purposes, and not for medical diagnosis. An ECG measurement that seems anomalous should not necessarily be any cause for concern with this home-made device, however medical attention should be sought if one is in doubt.

5.3. Audiometric test

Unlike conventional pure-tone audiometry which uses standardized earphones or headphones with calibrated headband force, a self-administered smartphone hearing test uses general commercial earphones which may be plugged loosely into the ear by pupils themselves. This may result in a large uncertainty in the thresholds obtained. Conducting multiple tests with the same student and setup allows for a calculation of the mean and variance, which motivates a discussion of the reliability of the measurement process. Conducting experiments whereby students can measure the frequency response of their own auditory perception apparatus not only motivates students but also fosters awareness of the fragility of the human ear and preventative practice for keeping the organ healthy (e.g., avoiding loud music).

5.4. Conclusion
During classroom activities, students found no particular difficulty conducting the experiments. Students spoke positively about both interest in the topic and perception of having acquired skills in physics and biology.

5.5. Note
The devices presented here are only for understanding the underlying physics concepts and should not be used for medical diagnosis.

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