At the Limit: Introducing Energy with Human Senses

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Energy belongs to the core ideas of the physics curriculum. But at the same time, energy is one of the most complex topics in science education since it occurs in multiple ways, such as motion, sound, light, and thermal energy. It can neither be destroyed nor created, but only converted. Due to the variety of relevant scales and abstractness of the term *energy,* the question arises how to introduce energy at the high school level. The aim of this article is to demonstrate how the concept of energy can become meaningful in the context of the human senses. Three simple experiments to investigate the minimal amount of energy that is required to generate a sensory perception are presented. In this way students can learn that even different sensory perceptions can be compared by using energy as the unifying concept.

Energy estimation skills

Students were given a questionnaire designed to determine their ability to estimate the scale of various physical quantities using everyday objects and activities. The assessed physical quantities were: length, mass, time, temperature, acceleration, speed, force, energy, power, and current. Over 200 grammar school students in grades eight to 10 (14–16 years) participated in the questionnaire. In addition, over 100 first-year college students took part as a comparison group.

In the evaluation of the questionnaires, the results concerning energy were particularly striking (see Fig. 1). Although 40%–50% of the younger students were able to determine the quantities' length, mass, and temperature accurately within one order of magnitude, only 6% of the students could give accurate estimates concerning energy. In the case of energy, students tend to be out (off?) by up to four orders of magnitude. The arithmetic mean of the energy estimates in our case is between three to four orders above the correct value, and the median between two to three orders of magnitude above. There is also a wide scattering of the estimates around the median. Even first-year college students show no significant improvement in their measurement estimation ability for energy.

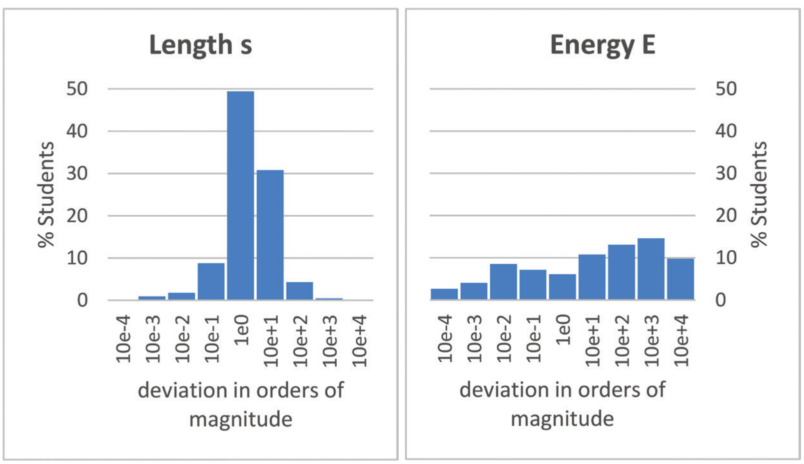

Fig. 1. Histogram of estimates for length and energy. Accurate estimates are defined as deviations within one order of magnitude. The results shown represent the average over the estimates of 230 students with seven questions concerning length and six questions concerning energy.

Energy and human senses

The questionnaire results indicate that students can estimate quantities better if they can connect them with sensual experiences. Quantities like mass, length, or temperature can be perceived by the human senses and are measured quantitatively in everyday life. Additionally, previous studies showed that students' interest in physics increases if phenomena that can be perceived by the senses are used in the physics classes.[1-4] Therefore it can be assumed that a combination of the energy content with a human body context can enhance the students' interest.

We propose to investigate quantitatively the connection between different kinds of energy and human senses. The sensual perception can be described as energy transfer between a source and the human senses. It can even be quantified by determining the minimal amount of energy that is required to generate a sensory perception (absolute threshold). By using the context "*absolute thresholds of the human senses*," the students get the possibility to gain practical experience with their own body of energy conversion and energy transfer during the experimental determination of their own sensory thresholds. Therefore, this context addresses the interests of the students, as well as practical activities in the physics lesson. Additionally, students can discover that extremely small amounts of energy are sufficient to generate sensual perceptions. This probably very surprising experience enlarges their sense of scale and can counteract against the dominating false estimation of energy.

Absolute thresholds for hearing, seeing, and feeling

Before determining the absolute thresholds of human senses, it will be beneficial to demonstrate a few characteristics of energy propagation. The strength of a sensual perception of sound or light depends on the square of the distance to the energy source, which can be conveniently demonstrated in a classroom with a balloon and a magic marker.

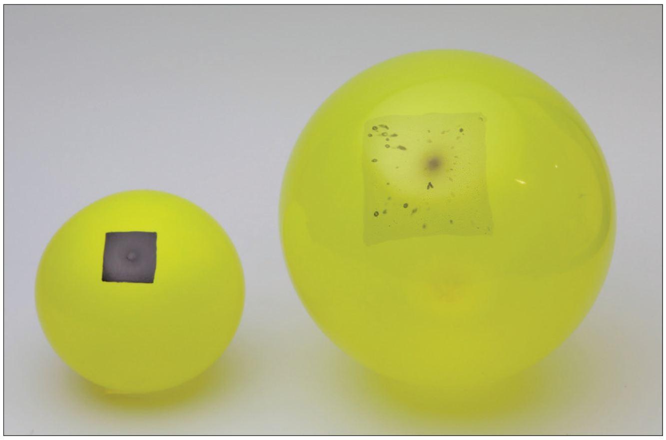

Fig. 2. Weak and strongly inflated balloon. By inflating the balloon, the area of the marked square increases while the color pales. The amount of energy per area that is perceived by the ear (eye) decreases to a fourth by doubling the diameter.

On the surface of a partially inflated balloon, a 2 cm x 2 cm square is drawn. The balloon is then further inflated until its diameter has doubled, at which point the square's area has increased by roughly a factor of four, while the intensity of the color has paled. In this context, the area of the original square is analogous to the area of the sensory organ (ear or eye) while the intensity of the color is analogous to the perceived intensity of the signal. In this way, students can grasp the inverse square law of energy propagation.

Thus the perceived energy $E_{perceived}$ at the ear or eye is scaled down over a distance r from the source energy E_{source} by the ratio of the areas:

$$E_{\text{perceived}} = E_{\text{source}} \cdot \frac{A_{\text{sensor}}}{4 \cdot \pi \cdot r^2}, \tag{1}$$

where A_{sensor} is the area of the sensory organ.

With these preparations, the absolute threshold for hearing, seeing, and feeling can be introduced. Only a few materials are needed for the realization: wood beads, drum, thin string, green LED (λ≈555 nm), absorption foil (e.g., grey overhead projector foil), lux meter or solar meter, stands, and other accessories.

The absolute threshold for hearing can be determined using a simple pendulum consisting of stands, a thin string with the length s_{string}, and a wood bead (m<1 g) pendulum mass [see Fig. 3(a)]. A drum is placed at the point of equilibrium of the pendulum. The absolute threshold for hearing can be calculated by determining the minimal deviation of the pendulum where a test person at a distance of two or three meters can still perceive the sound of the striking bead. The potential energy of the bead is given by:

$$E_{\text{source}} = m_{\text{bead}} \cdot g \cdot s_{\text{string}} \cdot (1 - \cos\alpha). \tag{2}$$

We assume that the potential energy of the deviated bead is completely converted first into kinetic energy and afterwards into an acoustic signal. Thus, we overestimate the threshold for hearing, since losses during energy conversion are ignored. However, since our aim is to provide a simple

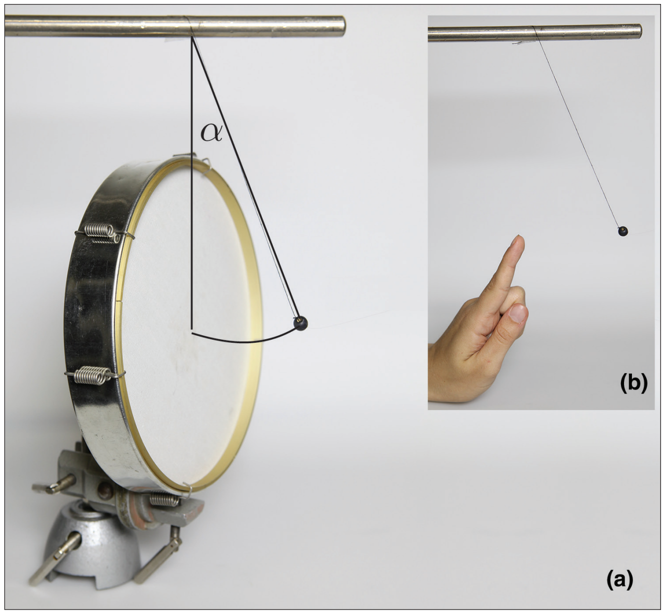

Fig. 3. Experimental setup for the determination of the absolute

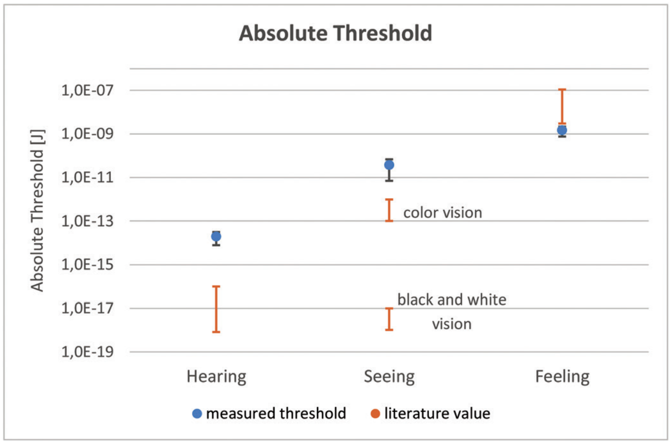

Fig. 4. Average results of the determination of the absolute threshold for hearing (2.0 x 10^{-14} J), seeing (3.8 x 10^{-11} J) and feeling (1.5 x 10^{-9} J) in comparison with literature values.[6,8-11] The absolute thresholds were determined by three to five student or teacher groups for each sense. The error bars correspond to the standard deviation of the respective measurements.

experiment for high school level, these simplifications are justified for a rough estimation of the energy threshold, as shown in Fig. 4.

The same pendulum can also be used to determine the absolute threshold for feeling [see Fig. 3(b)]. In this case the drum has to be replaced by the fingertip of a test person. Again, the minimal deviation of the pendulum by which the test person can still feel the collision of the bead has to be determined. Once more, we assume that the potential energy of the pendulum is first converted into kinetic energy of the pendulum, and afterwards completely transferred to the skin of the test person.

The absolute threshold for seeing can be determined with a green LED and several absorption foils (see Fig. 5). The LED is set up in a completely dark room at a distance of one

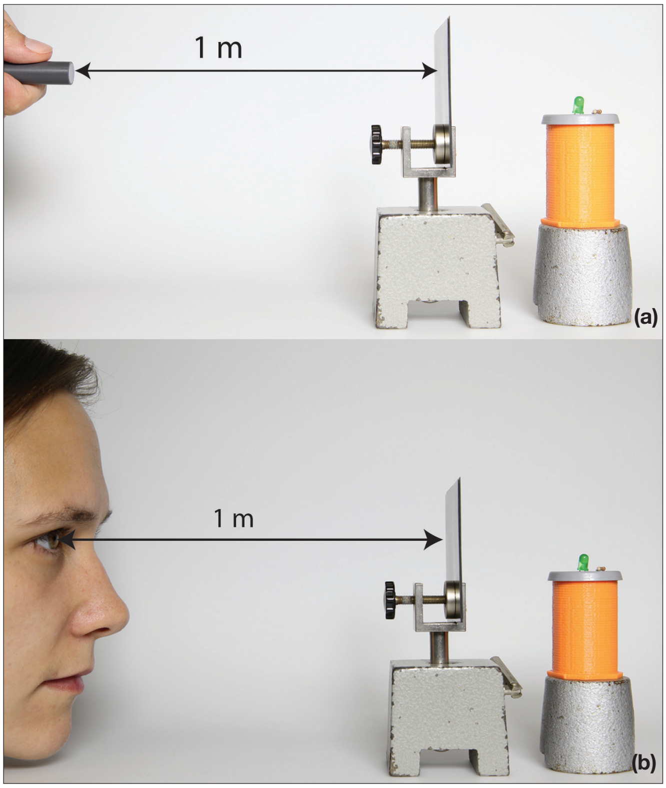

Fig. 5. Experimental setup for the determination of the absolute threshold for seeing with a lux meter (a) and with the human senses (b).

meter to a test person who observes it. Now the number of absorption foils in front of the LED will be increased successively until the maximal number of foils by which the test person can just still perceive the light of the LED is found. By measuring the irradiance P_I/A [W/m²] at the same distance to the LED as the test person with a lux or solar meter, the absolute threshold for seeing can be calculated with:

$$E_{\text{sensor}} = \frac{P_I}{A} \cdot t_{\text{summation}} \cdot A_{\text{sensor}}. \quad (3)$$

In this case the energy that is perceived by the eye of the test person not only depends on the irradiance of the source, the distance between the source, and the test person and the area of a human eye, but also depends on the temporal summation time of the human eye. Since the product of light intensity and summation time is constant (Bloch's law) for the absolute threshold, the summation time can be measured by variating the duration of the light flash.[5]

Results

For the calculation of the perceived energy, an approximated area of 1 cm² was assumed for the human eardrum and an area of the human eye.[6] The irradiance was measured with a lux meter and afterwards converted into W/m² (1 lx ≈ 1.46 $\times 10^{-3}$ W/m² for green light[7]). Measurements of the summation time resulted in a value of 0.1 s ± 0.03 s for seeing.

Several trials of these experiments with different test persons yield mean absolute thresholds of 1.5×10^{-9} J for feeling, 3.8×10^{-11} J for color seeing, and 2.0×10^{-14} J for hearing. The comparison with literature values for the absolute thresholds is summarized in Fig. 4.[6,8-11] During the measurements, constant experimental conditions were ensured.

Due to several simplifications a discrepancy between the measured thresholds and the literature values occur. In the case of hearing, an overestimation of the threshold is up to the assumption that the conversion from potential to kinetic and afterwards to sound energy takes place without losses. Additionally it was considered that the sound of the striking bead is completely in the audible range of the sound spectrum. Also the impact of the auricle, which focuses the acoustic signal, is neglected. Losses during energy conversion were also neglected by the determination of the threshold for feeling, as well as the influence due to the position of the receptors under the skin. In determining the threshold for seeing, the dark adaption of the eye was only partly considered, since it takes 10 minutes for cones to adapt to dark and about half an hour for rods to reach their maximal sensitivity.[12]

Another interesting fact is the theoretical limitation of the human senses by the physical properties of the observed phenomena. For the ear the theoretical limits are set by the Brownian movement of the air particles, which is in the order of 10^{-21} J,[13] so that the background noise caused by this movement is not detectable with the human ear. For the eye the theoretically limiting fact is the statistical fluctuation in the number of light quanta that are observed per time, which is in the order of 10^{-19} J for black-and-white vision.[14] In the case of feeling, the receptors are placed under the skin and the corresponding penetration depth to generate a sensual perception is 0.01 mm.[15] Therefore, the same results for the threshold can be determined by considering an elastic deformation of the skin by placing a small mass that is just perceivable on one's fingertip.

Conclusions

The introduced experiments can serve as a practical alternative or supplement to classical methods to introduce energy, energy conversion, and energy propagation in high school.

The context of the human body taps into known student interests and gives students a personal comprehension of the absolute threshold measurements, as well as practical activities in the classroom. The students can compare the sensitivity of their senses, since the energy serves as an invariant and universal scale. Another advantage of the determination of the absolute thresholds is the extension of students' sense of scale to extremely small energy values. The experiments allow for an estimation of the correct energy thresholds within one order of magnitude (Fig. 4). Comparing with the actual energy estimation skills (Fig. 1), this enlarged sense of scale can hopefully counteract against the dominating false estimation of energy by the students.

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