N O T E

Hearing Light

Manfred Euler *and* **_Kurt Niemann,_** Institute for Science Education (IPN), University of Kiel, Olshausenstr. 62, 24098, Kiel, Germany; euler@ipn.uni-kiel.de; niemann@ipn.uni-kiel.de, *and* **_Andrea Müller,_** University of Landau, Im Fort 7, 76829 Landau, Germany; muellera@uni-landau.de

I want to hear the scream of the butterfly.
—Jim Morrison

Students and even many scientists—as we found by asking colleagues—have no clear understanding of the performance of the human ear. Estimates of the minimum audible sound intensity often go wrong by more than 10 orders of magnitude. Somehow, the ear remains "terra incognita," although the auditory system is crucial not only for communication, but also for embedding us in a three-dimensional auditory space, allowing us to localize acoustic events without even being aware that we are doing it. Are there ways to engage students more deeply in experiments, discussions, and reflections on this important sensory channel and on the principles, which underlie its performance? In this note we focus on the sensitivity of the ear, concluding with an amazing home-built experiment that helps students gain qualitative insights on ear performance as well as on photoacoustic detection methods.

Visualizing the Sensitivity of the Ear

Under most favorable conditions ($f \approx 3$ kHz), an intensity of $I_0 \approx 0.5\ 10^{-6}$ W/cm^2 is audible.[1] Such tiny quantities require visualization. Assume an area for the ear canal of roughly 1 cm^2. In terms of total energy the hearing threshold corresponds to detecting a 10-W source at a distance of 1000 km, provided that no absorbing medium is in between. Imagine, for instance, "seeing" an energy-saving lamp that far off (Fig. 1). What an intriguing performance! The detection limit of the ear is comparable to the sensitivity of typical high-tech products such as microwave receivers in satellite dishes.

If the ear were a little more sensitive, we could "hear the grass grow," as we would say in German. Increasing the hearing threshold only a little further would bring us in direct contact with the atomic structure of the microworld. We could literally hear atoms by the noise they produce, when they impinge irregularly on the eardrum due to thermal motion. Evolution has driven ear performance to the physical limits. Unfortunately, such quantitatively more involved considerations are amenable only to students having a broader theoretical background. Are there more direct methods of demonstrating and experiencing the ability of the ear to detect tiny signals, which will convince lay people as well as less experienced students?

Such experiments do exist! Take Fig. 1 literally and ask your colleagues and friends if it is possible to hear light. After a short discussion on the soundness of your mental state, engage them in a bet. Wager that the sensitivity of the human ear is sufficient to hear the light emitted by an incandescent bulb. You will win! Of course, there is a minor trick! Here is the full story.

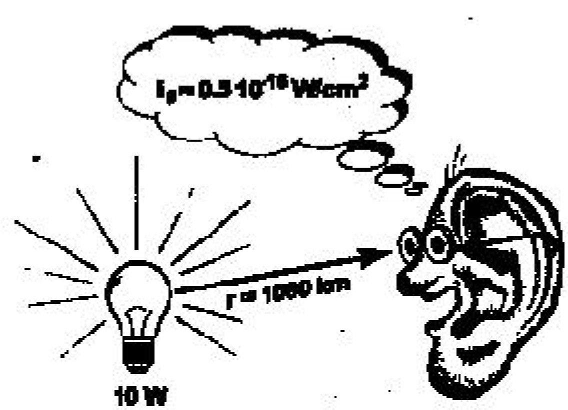

Fig. 1. Visualizing hearing threshold I_0 in terms of total energy.

Hearing a Pin Fall

Years ago, the metaphor of hearing grass grow inspired one of the authors (ME) to carry out a series of experiments in close cooperation with a friend's daughter. During a party with adults and children, the girl happened to be playing with a toy stethoscope from a toy "doctor's" set. However, listening to the imaginary heart sound of dolls was not that interesting. So both experimenters decided to investigate the sound of different objects. The toy instrument worked perfectly, and it came as a big surprise that it was possible to hear the sound of a hair knocking on the stethoscope's membrane. Compared with that, hearing a pin fall on the membrane almost sounded like a thunderstorm. An exciting experience —both for the young girl and the physicist! It was even possible to detect tiny scratches on the stethoscope's plastic membrane by moving the hair across the surface like the stylus of a record player.

By engaging the adults in these experiments, interesting discussions arose on the sensitivity of the human acoustic system and its power to detect individual sounds in mixtures of sound signals. They wanted to understand the physical principles, implemented by biological evolution to bring about a system with such intriguing physical and musical properties as our ear. Additionally, of course, more profane questions were also discussed; e.g., is it possible to hear the coughing of fleas or the scream of the butterfly? (Jim Morrison's music was around at that time.)

An important lesson can be learned from this event, which engaged both children and adults in hands-on, ears-on, and minds-on activities. Using physics in a self-reflexive context for better understanding of sensory processes and the "physics in our heads" may even stimulate the interest of people who express a deep dislike of physics, dating back to bad school experiences with the subject.

Rediscovering the Photoacoustic Effect

Another interesting (re)discovery was made by chance. The hair-scratching experiment was carried out in close proximity to a light bulb, in order to control the scratching process visually. A distinct hum could be heard when approaching the bulb with the stethoscope at a distance of 10 cm and less. The hum disappeared when the bulb was turned off or when the light flux was interrupted manually. The tests were quite conclusive—the human ear (equipped with a suitable stethoscope) is able to perceive light, provided that the light flux varies periodically, which is the case in ac-operated incandescent bulbs. So much for the bet.

What had been rediscovered at that party is the photoacoustic effect, first described by Alexander Graham Bell in 1880.[2] The sound is the result of a photo-thermal-acoustical transformation cascade. The toy stethoscope was equipped with a thin black plastic membrane. It absorbs light and transforms the energy into heat. Heat diffuses to the surface and dissipates into the surroundings. Thus the air in the stethoscope is heated up locally, creating a pressure increase. Since the bulb is operated by alternating current, each half-wave of the alternating current creates a pressure pulse. If the process is repeated periodically at a sufficient rate, the pressure variations produce an audible tone. However, there exist minor cross-cultural differences in rating the tones. People in the United States will agree upon hearing a 120-Hz tone, whereas Old World experimenters by some strange socio-cultural and technical conspiracy will perceive a tone of only 100 Hz.

Being able to "hear light" in that experiment is primarily not a matter of the ear's sensitivity but of its ability to detect rapid variations. Although the eye's inertia precludes seeing the periodic light fluctuations in ac-driven light bulbs, the ear can easily detect them after photoacoustic conversion.

Photoacoustics: History and Recent Applications

Based upon the experience gained during this experimental prelude, the question "Is it possible to hear light?" has often been posed in seminars for prospective physics teachers; resulting discussions proved to be very stimulating. On one hand, students engage in discussing the complex function of the ear as an acoustical sensor system and the physical limits of its performance. On the other hand, it turns out that the issue of photoacoustic conversion is not as straightforwardly resolved as we might expect. Many students tend to ascribe the photoacoustic action to momentum exchange of the photons when they interact with the membrane. Even after discussing the related radiometer experiment, the photoacoustic conversion process still remains a matter of controversy.

Students are in good company. Bell himself explained the working of his 'photophone," by assuming that the rubber diaphragm, which covered the entry of a hearing tube in his experiment, was heated and cooled periodically. He ascribed the thermoacoustic conversion to a periodically varying bending of the membrane, an explanation supported by calculations of Lord Rayleigh.[3] Soon after Bell's discovery, it was demonstrated that the effect is not confined to solids. It is also present in liquids and gases, rendering Bell's first explanation obsolete. (See Ref. 4 for historical background information.)

The historical development is a good starting point to design and discuss experiments in favor of or against proposed models. From there, it is easy to enlarge the view towards modern developments, e.g., photoacoustic spectroscopy and applications in health or environmental physics. Photoacoustic analyzers using a periodic stimulation by laser and sound detection via microphones allow the detection of gas traces to an extreme sensitivity. A most recent example demonstrates the power of the photoacoustic method to detect—online and in a noninvasive way—skin damage during sunburn.[5] The air we exhale carries a lot of information on the biochemical processes going on inside. Even after two minutes of exposure to ultraviolet light in a solarium, the exhaled air is shown to contain traces of ethene, a biochemical indicator of cell damage due to lipid peroxidation in the exposed skin. The method even allows an investigator to detect adaptation of the skin to ultraviolet exposure.

Hearing Light with Kitchen Equipment

From this noninvasive high-tech medical application we return to everyday experience. In one seminar this question arose: Is it possible to design a photoacoustic converter with everyday equipment replacing the stethoscope? After some discussions and intermediate experimental stages using cans equipped with diaphragms, and trying out blackened glass vessels equipped with rubber hoses to connect to the ear canal, we arrived at the solution shown in Fig. 2.

Take an empty (~ 500 ml) pickle jar and make a hole in the metal lid. Jar size and shape are not critical. Light a candle and bring the flame to the glass wall from the inside, in order to precipitate soot. Try to cover half of the inner surface with soot but leave the opposite glass wall transparent. Put the lid on the jar and hold the hole tight to your ear. Let the light of an ac-powered 60-W bulb shine on the soot-covered inner surface through the transparent opposite half of the jar. You will clearly hear the sound of periodically pulsed light from the ac-driven bulb via photoacoustic conversion.

Fig. 2. Can we hear light? It is possible to hear the hum produced by an ac-powered light bulb after photoacoustic conversion. Kitchen equipment will do!

From Low-cost Everyday Physics to Biological Hi-tech

This high-potential, low-cost little experiment provides the opportunity for interactive engagement, a key for learning successfully. The experiment is useful in counteracting misconceptions, such as the widespread conviction that biological sensor organs are rather crude and imperfect systems. On the contrary, in spite of certain limitations, they can compete with commercial systems. By demonstrating the unexpected ability to hear light, we are forced to think more deeply about the underlying "everyday physics" that we take for granted and which we use in an unconscious way. Investigating the ear's sensitivity is only a first step towards an understanding of the highly complex auditory system. Such an approach connects physics (both on basic and highly advanced levels) with cognitive processes, requiring an integration of physical, physiological and psychological investigations. Furthermore, such inter- and transdisciplinary questions can be discussed in the context of binaural hearing,[6] another intriguing example of everyday physics.

A more refined version of the experiment, using hands-on resonance to improve the performance of the photoacoustic converter cell, is under development.

Acknowledgment

We have to thank Dean Zollman, of Kansas State University for valuable discussions.

References

1. E. Zwicker and H. Fastl, *Psychoacoustics*, (Berlin, 1990), ***p. ?? (Au: please complete reference)***
2. A. G. Bell, *Am. J. Sci.* **20**, 305 (1880)
3. Lord Rayleigh, *Nature* **23**, 274 (1881).
4. For a history of the photoacoustic effect and modern applications see www.fys.kuleuven.ac.be or J. Thoen et al., *Physicalia Mag.* **15**, 273 (1993).
5. Harren et al., *Appl. Phys. Lett.* **74**, 1761 (1999).
6. W. M. Hartmann, *Phys. Today* **52**, 24 (Nov. 1999).