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Progress in Physics (68)

Physics Education Research - An Applied Science (part 2)

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3 Tasks and Services of PER

3.1 Evidence-based (Science) Education

No one would think of getting to the Moon or of wiping out a disease without research. Likewise, one cannot expect reform efforts in education to have significant effects without research-based knowledge to guide them.
R. J. Shavelson & L. Towne (Eds.) [77].

Evidence-based practice in general is the approach to base decisions on the best available evidence, in the sense of the best possible – in particular systematic! – use of existing knowledge and research. Evidence-based (science) education (EB(S)E) follows the example of evidence-based medicine, i.e. "[t]he conscientious, explicit and judicious use of current best evidence in making decisions", as one of its pioneers put it [78].

This is the same basic idea than the "scientific approach to science education" advocated in sect. 2, and indeed in the last two decades, it has led to a very strong current of research and practical implementation of EBSE: For the background in educational science in general work by Hattie [58, 79], based on more than 800 meta-analyses (comprising more than 80 Mio. individuals) is highly influential. Other useful sources are e.g. the "Best Evidence Encyclopedia" of the John Hopkins University [80], and work done at Stanford [77]. For physics and science education, in particular, there are world-class research programs [5, 81] and research syntheses and meta-analyses EBSE are available [82 - 86].

In physics and science education, the evidence-based approach has seen a very strong development in the last decades, and the idea has found strong support among many scientists interested in effective teaching and learning of their disciplines, including work finding recognition at very high level [15, 34, 38]. In particular, the physics Nobel Prize winner C. Wieman has devoted his work in the last decade to PER, [5, 6, 87, 88].

As a word of caution, however, it has to be emphasized that one has to be aware of debate about EB(S)E, raising also critical points [89]. It is certainly not the claim of EBSE to guarantee all by itself a solution to all problems in science education; simplistic recipes are not a goal one is looking for.

Within this rationale, Physics Education Research has the task to contribute to evidence-based decisions, development, initiatives, and teacher education, as illustrated in the first part of the article for the aspects of measurement (e.g. concept tests), interventions (e.g. motivating contexts; active learning approaches for lectures) and influences (e.g. gender). Further examples will be given below.

3.2 Teachers, and Teacher Education

The remarkable feature of the evidence is that the greatest effects on student learning occur when teachers become learners of their own teaching.
J. Hattie [79]

Teacher education has a pivotal role in an educational system: as studies on university level, it is the last stage of an educational trajectory, and at the same time is the basis and starting point for the educational quality for many generations of school students [90].

In order to respond to this pivotal role, it is clear that physics teachers have to be well informed about effective approaches of supporting interest and learning among their pupils, about their relative strengths (sect. 2.2), and about important influencing factors (sect. 2.3). Moreover, they have to be trained to use methods to measure the impact of their teaching (and possible changes) on pupils' motivation and learning, in particular regarding diagnosis of learning difficulties, and the potential impact of methods to overcome them (sect. 2.1). In the sense of Hattie's quote above, taking account of EBSE in teacher education provides a systematic and conscientious base of best evidence for teachers to "become learners of their own teaching". It is a main task of PER to provide a sound physics teacher education and continuous professional development in that spirit. This is well formulated by Robin Millar, a leading physics education researcher in a well-balanced statement [91]: "*We need to work towards a situation in which research evidence is routinely an explicit input to teachers' decision making, but where it is also accepted that this must be weighed judiciously alongside other kinds of knowledge to reach a decision that can be rationally defended.*"

Another reason for the pivotal role of teachers, besides effectiveness, is found at the (inter)personal level. The British UPMAP study (Understanding Participation rates in post-16 Mathematics and Physics) clearly showed that students' relationships with teachers (and other adults) has a decisive impact – through encouragement, advice, or acting as a role – on their decision to choose the subject physics after their mandatory schooling. One example of this from the qualitative data collected for UPMAP is given by [92] in the form of an insightful contrast of good and bad physics teachers, see Figure 5. The studies arrives at an unambiguous conclusion: "*In every case of an undergraduate reading [i.e. studying; AM] physics, their narrative tells that an adult has been significant in their becoming a physics undergraduate. Not peers, not enrichments, interventions or events, but some adult person or people – usually teachers or family members*". This result is complemented by the quantitative results [93] where encouragement is found to be the

Statement about a good science teacher [92]

I: Going back, you said you had a very good teacher at GCSE, what was good about him or her?
S: She was very good at making it interesting, she made the lessons fun and I suppose I got on with her on a personal level so that helped and she was very encouraging.

The same female pupil about a bad science teacher:

S: He was bad because he didn't know my name for maybe nine months and he didn't pay any attention… it got to a point where I wouldn't go to the lessons sometimes and would teach myself from the books.

Statements about the importance of role models [94]

"My math and science teachers were always important role models in my life. My parents wanted me to go into business or something like that."
"I think that one of the reasons why I chose math and science and chose engineering was because I had a teacher that was female. So if there was more females in engineering that could teach, it would make a big difference."

Figure 5: Encouragement, advice, role model: Importance of science teachers on the (inter)personal level, according to female students (I: Interviewer, S: student).

teacher variable with the strongest influence on the choice of physics (correlation $r = 0.5$), well ahead of all other factors. UPMAP is one of the broadest studies on this question (qualitative and quantitative student parts, $N > 5000$), and its results agree with the state of knowledge drawn from many other studies. When it comes to choosing an academic or vocational career in STEM (Science, Technology, Engineering, Mathematics) fields, research [94 - 98], including taking into account female students' own reports [95], consistently shows that discipline-specific self-concept is a decisive factor, as well as the availability of role models for [female] school students and students. See Figure 5 for a few more statements supporting this.

In line with the decisive role of teachers, the UK Institute of Physics (IOP) has developed in the last decades exemplary programs for initial and continuous physics teacher education [99]. In German speaking Switzerland, SWISE [1] has provided support for the improvement of teaching for general Science and up to secondary level I. The Swiss Physical Society, with a financial support by SCNAT, has recently initiated first steps towards a program for Swiss Physics Teachers.

1 Swiss Science Education, https://swise.ch/

3.3 Development

Another important task of PER is the development of new and innovative teaching and learning materials and ideas on all educational levels. A first type of this kind of work is the development of new experiments for educational purposes, with a range between surprising effects and insightful, in-depth analysis (Figure 6, a and b; respectively). Closely related is a second area – hands-on and "everyday" physics (physics of everyday phenomena), such as the famous "Flying Circus of Physics" by J. Walker [100], "La Physique du Quotidien" by I. Berkes [101], or the work by H.-J. Schlichting [102]. Figure 6c shows a nice simulation experiment of a potential explanation of the Bermuda triangle myth; even though today one knows that there is no conspicuous number of disasters in this high-traffic area, the example shows how physics can provide natural explanations without invoking any hocus-pocus.

Third, innovative approaches using new technology, such as ICT and multimedia, but also e.g. thermal cameras (see e.g. Figure 6b and extended work by Vollmer, see e.g. [107]). A recent review [108] presents almost 500 contributions oriented towards physics teaching practice from 10 European countries, with a perspective of finding ways of cross-language and cross-country use of the educational potential of this wealth of work. A particularly strong and stimulating development of the last decade is the use of smartphones (and tablets) as portable laboratories (see e.g. article series in "The Physics Teacher", [109]). They allow to extent physics education from the classroom to almost everywhere, where learners can investigate scientific phenomena in real life contexts (see 2.2). This covers a whole range from standard topics of physics education (inclined plane, rotations, energy conservation in novel settings (e.g. vertical jump, [110]) to more explorative experiments such as about knuckle-cracking (Figure 6d, [106]), pressure wave in tunnels [111], oscillations of elevators [112], and more, and from school to university [113]. Beyond a wealth of physics applications provided by this approach, recent PER studies have also provided evidence about positive impact on learning and motivation [114, 115].

A fourth important area of development are simplified approaches to interesting, but partially difficult topics, in particular modern physics, i.e. offers for physics communication ("popular science") and education. This requires a detailed

American Journal of Physics (U*(**))	Forinash, K., & Whitten, B. (2019). Resource Letter TEP-1: Resources for Teaching Environmental Physics. Am. J. Phys. **87**(6), 421-432. Henderson, C., Khan, R., & Dancy, M. (2018). Will my student evaluations decrease if I adopt an active learning instructional strategy?. Am. J. Phys., **86**(12), 934-942.
Bulletin de l'union des physiciens (BUP) (S*)	Médjahdi, K. (2018) Durée de vie d'un état excité... au lycée ! BUP (112) 1325-1332
Der Mathematisch-Naturwissenschaftliche Unterricht (S*)	Böttche, B. (4/2018) Über die Lebensdauer von Seifenblasen - eine Exponentialverteilung im Experiment. MNU **71**(4), 239-241
European Journal of Physics (U*(**))	Seyfarth, A., & Schumacher, C. (2019). Teaching locomotion biomechanics-From concepts to applications. Eur. J. of Phys. **40**(2) 024004
Physical Review – Physics Education Research (U**)	Wulff, P., Hazari, Z., Petersen, S., & Neumann, K. (2018). Engaging young women in physics: An intervention to support young women's physics identity development. Phys. Rev. PER **14**(2), 020113.
Physics Education (S*)	Bezerra, A. Z. L. N., et al. (2019). Using an Arduino to demonstrate Faraday's law. Phys. Educ., **54**(4), 043011.
The Physics Teacher (S, U*(**))	Babbs, C. F. (2019). Stone Skipping Physics. The Physics Teacher, **57**(5), 278-281.

Table 3: Some useful journals in the area of physics education with an example of a current contribution of interest (S, U: school and university level, respectively; focus on development and research**)*

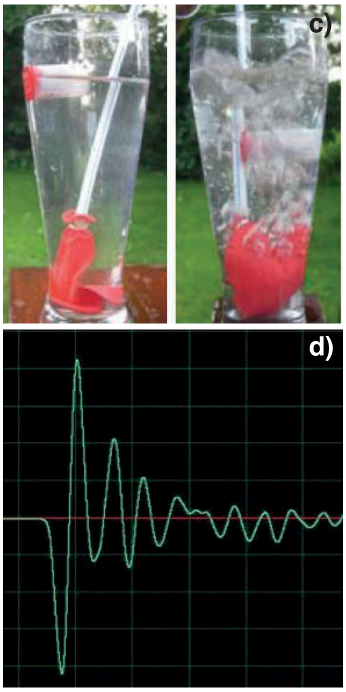

Figure 6: PER and development of teaching ideas
a) Interleave the pages of two paperback books in a way that the pages of the one book overlap with those of the other by at least 10 cm (card players know a similar way of shuffling). Now try to pull the books apart as shown – it is impossible! [103]
b) IR images and selective absorption for a plastic curtain (an analogy to IR images looking behind the "interstellar dust" curtain of the milky way [104]
c) Bermuda triangle analogy experiment: decrease of buoyancy by gas bubbles [105]
d) Knuckle cracking – actually an oscillation in the kHz range (recorded with smartphone app) [106]

understanding of the previous knowledge, conceptual obstacles, and a realistic difficulty level for different target audiences, which can be provided by PER (see 2.1). In view of attracting young people to physics related school programs and careers, educational material for high schools is of particular interest (see e.g. next section for activities and a book on cosmology and general relativity for (senior) high school, and Table 3 for some other recent examples of this kind from PER journals.

3.4 Service

Last, but not least there are various kinds of services PER has to render to physics departments and institutions. A very important topic for this is their engagement for science communication, and in particular for encouraging young people, in particular women, to study physics. PER can advise on evidence – good practice and research – from other institutions, provide ideas and suggestions for promising initiatives, and eventually help to evaluate them once realized. It goes without saying that strong cooperation with science communication units is a strong factor of success. Some examples:

First, programs of anticipated studies as those offered in Germany and in Switzerland by the University of Geneva (program "Athena" [116])[2]. The idea is to open regular university courses to pupils of the last classes before the matura, with the aim of offering an opportunity of exploration, orientation and inspiration for university studies in physics (and other disciplines). These programs work quite well, as e.g. indicators from the Athena program show (see Figure 7, [116]).

Second, input and support for out-of-school learning offers such as the S'CoolLAB of CERN or the other examples in Table 4, which provide a broad and high quality spectrum of different foci and formats, with the aim to foster a positive attitude and understanding of science among the population in general, and young people in particular. The input and support provided by PER concerns educational concepts, evaluation, realisation of projects, and funding requests. In this sense, a series of PhD theses at or in cooperation with the PER group in Geneva looks into evaluation and optimising design of out-of-school learning offers; for the S'CoolLab it could e.g. be shown that current interest and conceptual understanding (focus: electromagnetic fields, particles, radiation) are notably increased ($ES = 0.59$, $ES = 0.75$, respectively; [117]). A particular offer of cooperative out-of-school learning offer is the Stellarium Gornergrat (Figure 7b), a

2 Frühstudium (D): https://www.telekom-stiftung.de/projekte/fruehstudium; Athéna (Unige): https://www.unige.ch/sciences/fr/faculteetcite/programme-athena/

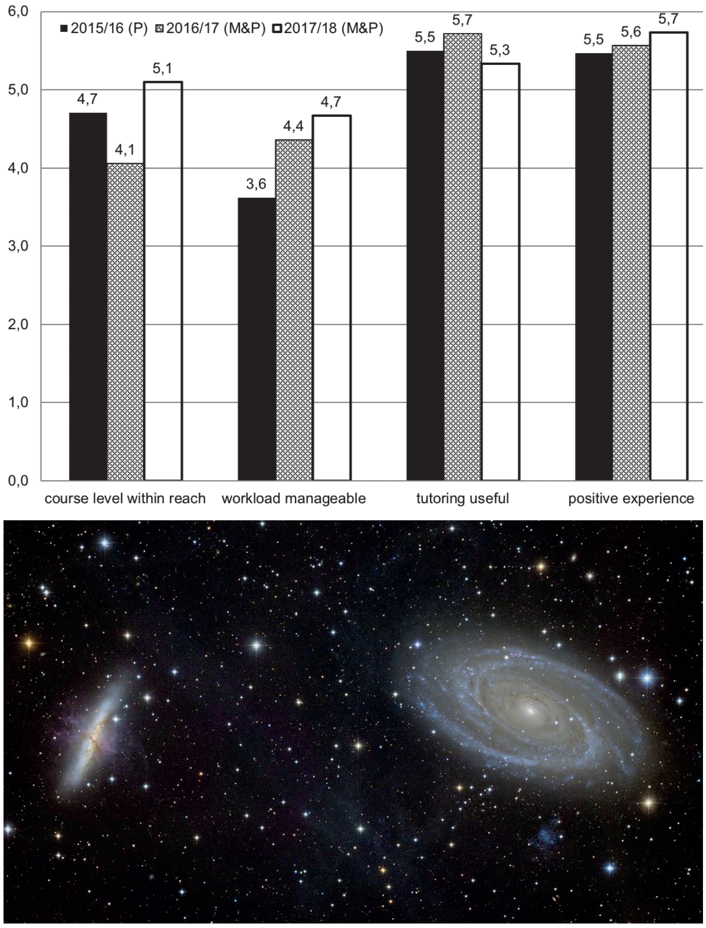

Figure 7: PER service to physics departments and institutions
a) Basic indicators of feasibility and impact of the Athena program according to average responses by participants (scale from 1= lowest to 6 = strongest consent; P: physics, M: mathematics)
b) Image from the module „Galaxy Zoo" of the Stellarium Gornergrat, an offer of largely unprecedented quality for educational purposes.

DeltaX: science education lab for lower and upper secondary level and physics, chemistry or biology	Helmholtz-Zentrum Dresden-Rossendorf *https://www.hzdr.de/db/Cms?pNid=1623*
iLab: science education lab mainly for lower secondary level and physics, close link to PSI research (e.g. combination with guided tours)	Paul Scherrer Institute, Villigen *https://www.psi.ch/de/ilab*
mobiLLab: mobile high-tech laboratory with 12 work stations for lower secondary schools	Teacher University St. Gallen *https://www.phsg.ch/en/research/projects/mobillab*
Scienscope: science education and outreach centre for all age groups and 7 scientific disciplines (chemistry, biology, earth sciences, informatics, mathematics, physics and astronomy)	Faculty of Science, University of Geneva *https://scienscope.unige.ch/*
S'Cool LAB: physics education lab with a focus on CERN-related physics for upper secondary level	CERN, Geneva *http://scool.web.cern.ch/*

Table 4: Physics and science out-of-school learning offers

remote-access observatory for educational purposes run in cooperation by astronomers in Bern and Geneva, and the Geneva PER Group, which exploits the high motivational potential of astronomical topics (see 2.2) by integrating them in regular physics (and mathematics) lessons [118]. This work is carried out by an active high school teacher, Stéphane Gschwind, who is key to ensure adaption to the target audience (content difficulty, language level) and to study plans, for testing activities in test classes, for support to collegues interested to use the Stellarium, for continuing development courses and for actively promoting the project through professional networks.

Third, cooperation within the "communication/education" sections of large national and international research programs. For instance, within the National Centre of Competence in Research (NCCR) SwissMAP (The Mathematics of Physics, [119]), there was a request for an educational project launched on the occasion of the centenary of Einstein's general theory of relativity. Alice Gasparini, physicist and active high school teacher, has developed a learning sequence about cosmology and general relativity for high schools students providing access to the essential physical ideas of these fascinating topics, strictly using mathematical tools available at school. All material is accessible for teachers at a website, and also as a printed book [119 - 121].

4 Conclusions, Perspectives

As shown by the examples above, evidence-based approaches in PER – measurement methods, results on teaching interventions and understanding of influences – play an essential role in science communication, teaching practice and teacher education in our discipline. As stated several times, they are proposed as examples of good practice, but it is not claimed that they are ideal, nor the only ones. Moreover, there are important aspects which were not discussed in this article due to lack of space, especially the extremely fruitful connections between physics education and history and philosophy of physics, e.g. the many interesting contributions in this journal [122], in particular by J. Lacki, or the very nice book for the general public on the conceptual underpinnings of quantum information theory by N. Gisin [123].

As an applied science, PER systematically links research with development and other practical tasks and services (see examples in sect. 3). PER is about research-based development, and practice-inspired research in the area of physics education. These two elements sometimes face prejudice from scientists. On the one hand, it is not uncommon that scientists believe that physics education is an opinion based rather than an evidence-based discipline. On the other hand, few have first-hands experience with the application of PER results in their own teaching practice. They might thus not be convinced of their usefulness. It was one purpose of the article to provide arguments and examples that the prejudice mentioned is unfounded.

Research-based development, and practice-inspired research in the area of physics education are not unimportant objectives, nor trivial ones. A major obstacle is insufficient interaction between research and (teaching) practice. For instance, in the review on ICT uses in physics teacher journals [108], less than 10% refer in any form to underlying educational research (e.g. potential to overcome misconceptions or to foster motivation). ICT application in physics education is a technologically highly innovative area, but it appears as largely disconnected from physics education research – something unthinkable in engineering or medicine. One condition to overcome this "implementation gap" is a strong and systematic cooperation of PER with active teachers, in research, development and teacher education.

Another condition is about the role of PER in academic structures. If universities, as strongholds of culture and science in a society, want to ensure the transmission of their values and knowledge, in order to have good students and to ensure the academic succession, but also for the development of society in general, they have to strongly engage themselves for Evidence-Based Education, in particular concerning teacher education. This implies a systematic and reliable positioning of physics (science) education in academic structures, either by PER groups integrated in physics departments, or by institutional partnerships between physics departments and physics/science education groups at teacher education universities. This is the only way to ensure continuous integration of modern physics, cooperation for outreach initiatives of physics institutions, long-lasting collaborations with active teachers and a research basis for physics teaching at school and physics teacher education, and thus to ensure educational quality for many generations of school students.

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