PATHWAYS – A Case of Large-Scale Implementation of Evidence-Based Practice in Scientific Inquiry-Based Science Education

Sotiriou, Sofoklis[1], Bybee, Rodger W.[2] & Bogner Franz X.[3]

[1] Ellinogermaniki Agogi, R&D, Pallini, Athens, Greece

[2] Biological Science Curriculum Study, Executive Director (retired), Pikes Peak Research Park, Colorado Springs, CO 80918-3842, U.S.A.

[3] University of Bayreuth, Centre of Math & Science Education (Z-MNU), Chair of Biology Education, University Campus, NW-1, D-95447 Bayreuth, Germany

Correspondence: Bogner Franz X., University of Bayreuth, Centre of Math & Science Education (Z-MNU), Chair of Biology Education, University Campus, NW-1, D-95447 Bayreuth, Germany

Received: January 14, 2017 Accepted: February 7, 2017 Online Published: February 27, 2017

doi:10.5430/ijhe.v6n2p8 URL: https://doi.org/10.5430/ijhe.v6n2p8

Abstract

The fundamental pioneering ideas about student-centered, inquiry-based learning initiatives are differing in Europe and the US. The latter had initiated various top-down schemes that have led to well-defined standards, while in Europe, with its some 50 independent educational systems, a wide variety of approaches has been evolved. In this present paper, we portray a European bottom-up initiative, “PATHWAY to Inquiry Based Science Education”, to define a basis for learning initiatives and to meet current challenges to access learning, to share knowledge and establish competences in learning communities. Our approach was designed to act as bottom-up catalyst by mobilizing teacher communities to (further) foster inquiry. Of a sample of 10.053 science teachers from 15 European countries (incl. Russia), about 5060 provided empirical support for our teachers’ professional development initiative. The response pattern portrayed teachers’ preferences and pointed to potential needs in professional development (PD) efforts. On average, our sample reported an altogether 11 years’ period of teaching practice in general but just 2-3 years of experience in inquiry-teaching. In the view of that, consequences for professional development (PD) initiatives are discussed.

Keywords: Professional Development (PD), Inquiry-based science education, Large-scale, Teacher community, European educational diversity

1. Introduction

To understand scientific inquiry and its potential, science and inquiry need separate consideration. Science provides empirically supported explanations. To be clear, science does not and cannot explain everything, but it can supply dependable knowledge that may help individuals to understand the world in which they live. Scientific knowledge is more than an accumulation of disconnected facts; indeed, it presents concepts with explanatory power and often provides some understanding of cause and effect as well as the power to predict, react or control. Despite of all the existing valid and reliable knowledge, individuals’ everyday ideas are often challenged by reality (*e.g.*, Lakoff & Johnson, 1999). For non-scientists, it may be difficult to accept, for instance, that all substances consist of tiny particles held together by electrical forces.

Science teachers, besides the need of a solid knowledge basis, must decide on an effective way to teach an issue, given the difference between what students’ knowledge and accepted scientific explanations (Gilbert & Pope, 1986). Science is more than a body of knowledge; the issue of what we know, and of what we mean by scientific inquiry, is regarded as a function of processes by which scientists acquire that knowledge. Scientific inquiry uses processes (such as observations and/or experiments) that yield empirical evidence. It is not the authority of individuals, the dogma of religions, the doctrines of governments, or the power of private enterprise that carries weight in scientific explanations. Rather, it is the power of empirical evidence, critical analysis, independent confirmation and careful inference derived from observations and experiments leading to scientific explanations (*e.g.*, Driver et al., 1994; Keselman 2003; Kuhn 2005).

The prevailing misconception of the public, of most textbooks, and, unfortunately, of some science teachers, sees science as a systematic method with variations on the following procedure: first, state a problem; second, form a hypothesis; third, perform an experiment; fourth, analyze data; and finally present a conclusion. However, science students are often being told about science and asked to remember facts rather than to learn how to think scientifically (Alberts, 2009). "Inquiry-learning" describes a cluster of learning and teaching approaches where inquiry or research drives the learning experience (Randler & Bogner 2009). Students actively engage by asking questions and by sharing their knowledge (gains). Hands-on experiments may provide a sound basis for formulating questions, for working with peers (sometimes in partnership with or moderated by teachers), and for applying the usual research techniques (*e.g*., Meissner & Bogner, 2012; Scharfenberg & Bogner, 2013). Inquiry processes may vary from highly structured to more flexibility, with a large degree of control in the framing and direction of inquiries to a more stretchy approach (Valanides & Angeli, 2008; Minner et al. 2010). The inquiry process includes learning tasks, assessments, resources, environments and teaching strategies designed to support learning via exploration and discovery – and it typically reflects strong commitment to student-centeredness and learner empowerment (White & Frederikson 1998). From the perspective of an inquiry teacher, a key challenge is to establish conditions where students can flourish and effectively develop relevant inquiry competencies (Shulman & Valcarcel, 2012).

Inquiry-learning has a variety of meanings (as a general method, as a teaching method, as learning strategy, etc.), and is regarded as a type of active individual learning with authentic research-like activities intended to explore, master and expand an existing knowledge-base (Hodson, 1993; Anderson, 2002; Fremerey & Bogner, 2015). Although implementing inquiry requires a longer learning time (as additional time for explanations and training abilities is needed), subsequent integration leads almost always to deeper understanding levels and longer lasting knowledge (Conradty & Bogner 2012; Schmid & Bogner 2015). Learners are supposed to become engaged producers of knowledge (Schwarz & White, 2005), and by that way to expand pre-existing knowledge (Renkl, Mandl & Gruber, 1996). The terms "inquiry-based learning" and "problem-based learning" (PBL) often are used synonymously (Bereiter, 2002) although the first is generally regarded as the broader concept, with PBL seen as a subset of inquiry-learning (*e.g*. Schaal & Bogner 2005). For example, PBL is often based on pre-established scenarios in acting as a stimulus for inquiry by following a fairly standardized procedure and including a wide variety of triggers. The term inquiry-learning, however, is often used to describe considerable freedom in directing individual inquiries in using open-ended questions and in focusing on learning techniques (e.g., Linn 2000; Pilkington, 2004; Kuhn 2005). As in classroom settings, students are often taught about science facts, rules and axioms, Osborne and Dillon (2008) complained that schools failed to provide a route into science for future scientists. The challenge, therefore, is to re-consider how individual solutions may fit and how to meet the needs of all students - those who will go on to work in scientific and technical subjects, and those who will not (Kali & Linn, 2009).

In our view, an appropriate classroom may provide authentic and even complex learning experiences by providing students with opportunities to participate in scientific practice, using the discourse of science and working in scientific environments (Sotiriou & Bogner, 2011). An innovative classroom may offer teaching adapted to individual needs in order to work more effectively in the classroom. Teachers need to accept the internet's potential to deliver interactive experiences that supplement traditional educational tools. The rich resources of scientific databases, eLearning tools and digital educational resources can act as catalysts for learning (Langheinrich & Bogner 2015). Outreach mediators such as research centers may offer suitable knowledge across scientific disciplines, provide assistance for understanding complex scientific research and make science understandable and interesting to the student. Attracting attention by presenting contemporary ideas and by offering activities closely related to both new technological achievements and everyday life are regarded as appropriate means to achieve adequate levels of understanding even of complex issues (Scharfenberg & Bogner, 2010). Offering advanced and highly stimulating "hands-on" experiments might encourage observations and subsequent conclusions instead of offering isolated occasional descriptions of such experiments (Sotiriou & Bogner, 2008).

Integration of inquiry into science classrooms started in the US by encouraging students to complete specimen collections by corresponding with collectors around the country, and thus provoking discussions about what science is and how it should be taught, by addressing "science as subject-matter and as method" (Dewey, 1910). The message became clear: requiring less emphasis for accumulating information loads but favoring methods of thinking and attitudes of mind: both abilities in inquiry and the nature of science became central foci of discussion (Schwab 1960). Simultaneously, the conviction grew that knowledge is more than a ready-made transfer requiring a habitual disposition of mind. Teaching methods needed to develop thinking and reasoning abilities, formulating habits of mind, learning detailed subject matter, and understanding the processes behind it. Inquiry became a prominent theme treating science not simply as stable truth that just needs verification, and that made science teaching in school classrooms inconsistent with modern science. Schwab (1966) described science teaching as a structure of discourse to create the acceptance of “the tentative as certain, the doubtful as the undoubted”. Finally, various top-down initiatives have led to well-defined standards applied throughout the country (Collins 1995; NRC 2011). As an appropriate tool to reach inquiry, hands-on experiments were recommended by considering three levels of interaction: (i) describing methods of investigations, (ii) providing laboratory manuals to help perform experiments and (iii) allowing autonomous explanation of phenomena. “Enquiry into enquiry” appeared as key to deal with problems, data management and interpretation and to reach conclusions as scientists do.

Scientific inquiry still needs wider implementation. Our knowledge about construction of individual knowledge is supposed to involve hands-on experience, though without separating or neglecting learning (Bybee, 1997, 2002; Donovan & Bransford, 2005). Learning is regarded as something that should become second nature and to build upon pre-knowledge to meet an objective (as it is the case, for instance, in practicing law) (Michaels, Shouse & Schweingruber, 2008). Scientific inquiry is one form of scientific practice, expanding and enriching the teaching and learning of science. In following this vision, European educational systems, because of long national traditions and dozens of languages, automatically produce heterogeneous outcomes. About 50 independent educational systems exist within 28 member states. This contributes to substantial variation in the methods employed to improve science education, such as inquiry-based learning, collaborative problem-solving, and exciting and relevant curricula. Within this environment, our European initiatives came into action by focusing on good practice (i) by bringing into classrooms rich digital resources based on real-world problems. By putting all resources together, testing ideas, receiving feedback, and working collaboratively beyond a conventional classroom environment may lead to sustainable conclusions. eLearning tools may additionally help to provide a framework to enhance learning, encourage problem-solving, support model activities, to guide practice, represent data in different ways, and to contribute to a systemic educational approach (*e.g.* Wu et al., 2013). (ii) By encouraging students to evaluate the quality of their own thinking and to allow revisions. (iii) By providing opportunities to interact with scientific environments and to receive feedback from them. (iv) By establishing and supporting (local and global) communities of teachers, teacher trainers, education policy makers, parents, scientists and other members of society in order to provide opportunities of becoming acquainted with environments beyond the school walls. This environment may help teachers to think differently about learning opportunities, may reduce barriers to students by offering new partnerships between teachers and students.

The objectives of our study were two-fold: (i) to highlight the European bottom-up approach based in the wide diversity of traditions; (ii) to present empirical conclusions from our European initiative, recruiting teachers all over the continent and initiating/accelerating methods of widespread inquiry in schools.

2. Methods & Procedures

To use the potential of inquiry-based education, individual fears and negative preconceptions need to be adequately addressed (Falik, Eylon & Rosenfeld, 2008). Implementing appropriate interventions may be effective tool in achieving this – coaching teachers in classroom practice, designing effective professional development programs, developing stronger teacher leaders, and enabling teachers to learn from each other. In our view, two key points need our full attention in such interventions: (i) Effective training in inquiry-based methods may lead to a major paradigm shift for teachers as they need to acquire new skills, abandon possible long-standing practices and move away from established “comfort zones” and become exposed to newly perceived risks. (ii) Help in changing individual behavior in the everyday routine by successively adapt the new vision.

A large-scale implementation of teachers’ PD activities with school environments, in science and research centers as well as in teacher training centers provided the successful basis (some example case studies are discussed in the next paragraphs) that have proven effective. As there is supposedly no single correct way to plan and implement professional development we indented to improve teaching by offering support within settings that present unique goals, strengths, resources and barriers. Effective implementation requires the blending of background research, practitioners’ wisdom, passionate beliefs and an adequate repertoire of strategies from which to choose in the classroom. Seeking maximum efficiency in supporting teachers, professional development needs flexibility without sacrificing efficiency. In our view, inquiry-based training needs to accomplish various requirements: (i) Encouragement to share knowledge with peers or experts. (ii) Support in problems-solving skills, *e.g.* by asking high-level questions and hypothesizing about unsolved problems. (iii) Application of alternative assessment methods. (iv) Customizing new activities for instance by making decisions on the level of inquiry. (v) Alignment of inquiry with the concepts taught in the classroom.

In review of these requirements, our approach aimed to improve school science education by addressing and updating teachers' current methodologies in terms of transferable knowledge, skills and competences. Thus, PATHWAY supported the use of inquiry-based teaching and ready-to-implement classroom strategies. Another important aspect was introduction and updating of teaching strategies based on a thorough incorporation of ICT to realize its full potential in the classroom. In addition, to measure the success of intensive projects involves the efforts of hundreds of training experts and thousands of trainee teachers.

Our PD activities provided opportunities for teachers to familiarize themselves with the new inquiry ideas, and to understand about barriers, to imagine situations of learners in classrooms before to adopt and adapt, as well as to reshape teaching practice. In our view, four key strategies may effect changes in teacher practice by treating them as adult learners and engaging them in learning programs based on current research:

(1) The "Evidence-Based" PD strategy

The major goal of this strategy line is to help science teachers develop expertise in the effective introduction of inquiry into their practice and to develop "scholarships of teaching" where teachers will learn from each other. This element is expressed in teachers' abilities to reflect, to present evidence, and collaborate with their peers and is considered an important aspect of creating communities of practice.

Case Example: School science and front end research

CERN high-school teacher programs aim to demonstrate a process for bridging the gap between the frontier research at CERN and science education and communication. The aim is to promote creative problem-solving, discovery, learning by doing, experiential learning, critical thinking and creativity. The three-week program hosts dozens of teachers, offering a deeper insight into particle physics through a variety of workshops. The program's overall aim is to help teachers to inspire students to follow careers in science. In the second week, they split up into working groups to evaluate CERN's educational tools or create new ones. The program emphasizes reflection on how science itself is done, by highlighting inquiry as a way of achieving knowledge and understanding.

Each program dealt with a central domain of science learning (e.g., inquiry in middle school science classes, inquiry in chemistry, particle physics, knowledge integration in physics, and learning assessment). A set of inquiry activities were required to implement appropriate activities in classrooms. Teachers became acquainted with such activities by experiencing them in three different modes: as learners in participating in inquiry-based learning, as teachers by implementing inquiry-based strategies, and as researchers. In the latter role, teachers collected and analyzed data about teaching and students' learning, and discussed the evidence collaboratively with peers. Finally, teachers prepared a portfolio documenting their practice. The results of the research conducted on this program showed that the strategy contributed to the professional development of teachers as they extended their both their pedagogical knowledge and their knowledge of inquiry teaching. Furthermore, anxiety scores relating to the implementation of the IBSE approach fell, as the teachers became more reflective and more aware of barriers and opportunities.

(2) The Teacher as Curriculum Developer

In this section, teams of teachers developed innovative instructional activities guided by facilitators. The teachers implemented activities in classrooms and assessed effects on students' learning: One example is a school-based PD program, such as "lesson study", or an out-of-school centralized context. The rationale followed the assumption that teachers are familiar with the design of instructional strategies, since this is what they do all the time. Following preliminary experience with the instructional approach (*e.g.* inquiry teaching), this strategy can promote teachers' pedagogical skills through the design of inquiry activities. This strategy may a 3-phases vision: a diagnostic phase where teachers determine learning goals based on students' prior knowledge; a preliminary design phase based on expert input, available resources, existing research findings, etc.; and an iterative third phase implementing activities, examining learning effects and subsequent revisions. Each phase culminates in reviewing students' work. The results showed that the strategy promoted teachers' knowledge of content, pedagogy, and the relevant science education literature (relevant research and practice). It stimulated teachers' creativity and led to diversification of the instructional strategies that they used in the classroom. There was a clear effect on teachers' practice as indicated by teachers' reports and the materials brought to the workshops. It also assisted in the formation of a community of learners.

Case Example: School science and science museum: Cooperation for improving teaching, learning and discovery.

This SMEC (School-Museum European Cooperation) aimed to encourage the use of a museum as an educational resource and to contribute to PD in terms of competence development of and expertise in using museums. The intention to bring together teachers and museums aimed (i) to create conditions in which complementary *competences together consider the use of museums as an educational resource facilitating inquiry-based approaches in classrooms; (ii) to exchange experience and expertise and enrich mutual knowledge of each other's education work; (iii) to devise joint pilot projects using museums for science education. The course has now been running for more than 5 years in the National Museum of Science and Technology "Leonardo da Vinci" (Milano) and the "Deutsches Museum" (Munich), where the collections, staff and educational programs are used as an integral part of the course activities.*

(3) The "Tutor-Teacher"-Strategy

This strategy focused on biology teachers and pre-service teachers in an outreach laboratory. In contrast to most outreach laboratories, in which the academic personnel teach visiting classes, this program offers a unique setting in which teachers and pre-service teachers learn to introduce scientific methodology in the classroom (Franke *et al*., 2013). A pre-service module is presented as a PD example.

Case Example: "GeneLab" outreach lab for Biotechnology and Genetics.

The target groups are secondary school teachers and pre-service teachers (i.e., university students of Biology education), and in-service teachers of Biology or of other subjects like ethics (Scharfenberg & Bogner, 2013a,b). Classes and their teachers attend a day-long experimental module in the GeneLab (offered during term breaks). Students increase their knowledge of key issues in molecular biology and gene technology and apply basic techniques. In parallel, science education research has provided a consistent evaluation of instructional efficiency (Scharfenberg & Bogner, 2010). All modules include authentic experiments such as Genetic Fingerprinting of students' deoxyribonucleic acid from oral mucosa cells; the polymerase chain reaction with a selected human mini-satellite sequence; and agarose gel electrophoresis of the isolated and amplified DNA probes. Additionally, students discuss (and evaluate) the pre-implantation diagnostics (PID) and their ethic-moral consequences (Goldschmidt & Bogner 2016, Goldschmidt et al., 2016). All modules conform to the current syllabus. The pre-service teacher module consists of six elements: First, pre-service teacher complete a half-day seminar on the specific content of the student module (by behaving as students; i.e., participating in parallel to school student groups as a separate group and completing all experiments). Second, under guidance, they take care of provision of the equipment in all work areas (a maximum of 32 students in groups of 8) acting as tutors to two student work groups according to the assignment assistance model of tutoring (Scharfenberg & Bogner 2016). Third, on the third experimental day, pre-service teachers switch to the teacher role (i.e., they teach one hands-on phase to the students). A final reflection seminar wraps up the module.

(4) The Blended Learning Strategy

Since IBSE teaching requires fundamental changes in teachers' views, knowledge and practice, a long-term perspective is needed. An on-line component added to face-to-face meetings may support teachers between meetings. The "Teacher as adult learner" paradigm plays a central role in the design of web-based PD programs. While in a "traditional" face-to-face program, teachers are a "captive audience", participation in an online voluntary learning activity is not guaranteed. The learning framework designed for such a program has to be highly relevant, and to consider the characteristics, motivations and barriers to learning of adult teachers. Garrison and Kanuka (2004, p. 99) argue that "blended learning is not just finding the right mix of technologies or increasing access to learning. Blended learning inherently is about rethinking and redesigning the teaching and learning relationship". A thoughtful redesign may allow integrating the strengths of both face-to-face and online components. This integration may engage teachers in critical discourse, reflection, continuous learning, and construction of knowledge.

Case Example: "Discover the COSMOS" series of inquiry workshops

The goal was to increase the leadership capacity of teachers, to demonstrate the potential of out-of-school programs to students at all levels. The fundamental philosophy builds upon the idea that questioning and curiosity are keys to understanding the world, and that inquiry is a critical approach to learning about scientific phenomena. The hidden syllabus was the belief that human beings are natural inquirers and that inquiry is at the heart of all learning. Science inquiry is regarded as a vehicle to increase participant's understanding of the true nature of the scientific process, and to develop an understanding of important science content. We believe that, along with other instructional methods, inquiry is an important component of the science education experience because it motivates students to further their conceptual study of scientific ideas and develop their investigation skills. Inquiry workshops are crafted to provide powerful and transformative experiences by immersing participants in the process of science inquiry. These experiences introduce participants to the special character of science—that it is at once a body of knowledge and a dynamic questioning activity. A primary focus of our work is to use hands-on investigation, *reflection, and group discussion to foster an understanding of the essential features and structure of inquiry, which participants can take back and share with colleagues in their home districts and projects. These experiences serve as a framework for designing strategies that can support the creation of classroom environments for students' inquiry. That model remains fundamental to our program development, providing us with a "laboratory" of real-life settings in which to study how to support inquiry-based approaches to teaching science. The programs and resources have been designed to support the development of an ongoing community of learners dedicated to fostering high-quality science education (Sotiriou, Neofotistos, Bogner, 2011).*

The monitoring process of a total of some 300 PD courses focused on a) the impact of the proposed approach on teachers' practice (immediately after and 4 months later) and on the impact on the students as estimated by their teachers. We used Likert scales to rate the options and reduced the 4-digit scale for reasons of simplicity to two levels (1+2 and 3+4 redefined as low and high degrees of fulfilment).

The sample consisted of 10.053 science teachers of a lively community to sustain a innovation process. About half the sample contributed to our data basis (n= 5060) yielding empirical support for the innovative potential of inquiry learning in science classrooms through effective community building and teachers' professional development.

3. Results

PATHWAY demonstrated how resonant leadership helps to focus on its own talents, strengths and genuine interests, thus helping to support professional life. Community-building allowed teachers to reach the level of know-how, resources and expertise from colleagues trusted for their expertise and reliability. Finally, new types of social interactions showed the collective reputation as a strong incentive to remain a member of the trusted network.

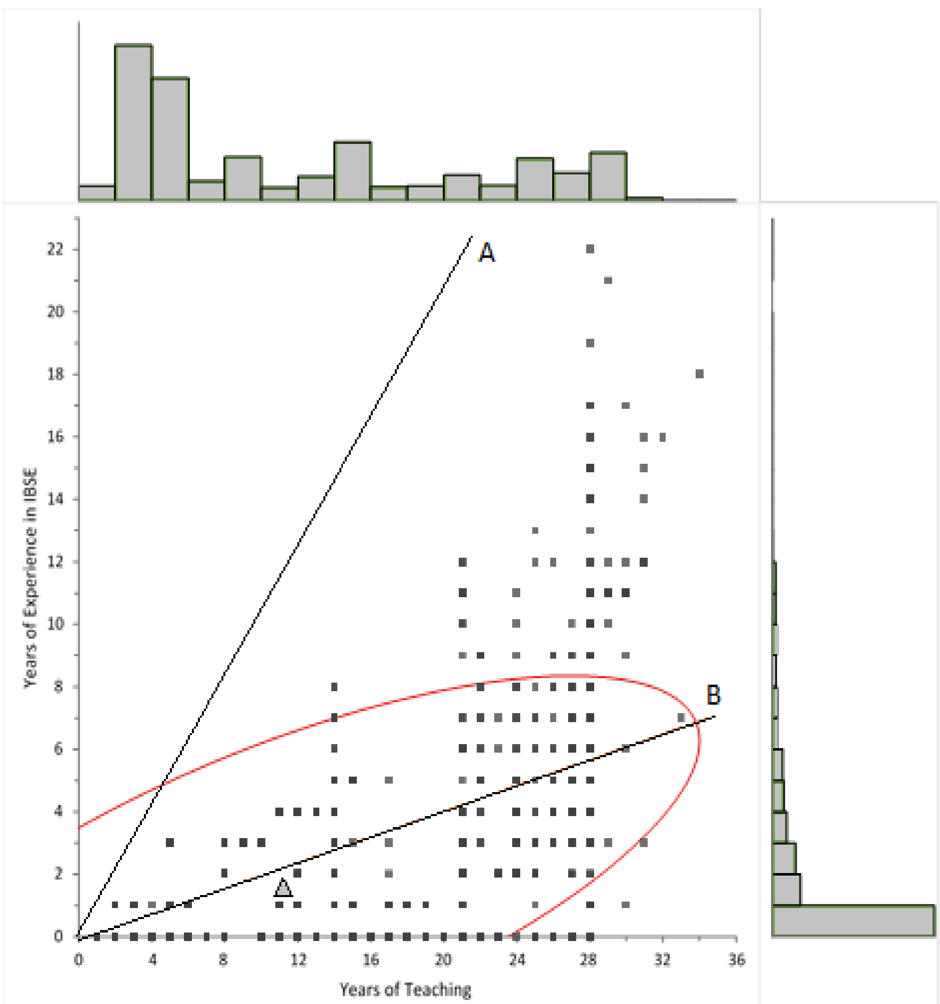


Figure 1. The scatter plot of Years of Teaching by Years of Experience

The red curve envelops 95% of our sample, the cross marks the average score of the total sample. The red line (B) displays the correlation between the years of experience of the 5060 participating teachers in the training and their experience in implementing inquiry process in their lesson (in years). On average, teachers have limited experience in implementing inquiry (less than 2 years) for about 11 years ( ) of teaching service (grey boxes (right edge) represent the number of teachers within the years of experience). As expected, our sample demonstrates a behavior that is far from optimal (A: time that the inquiry approach is implemented at the same level with the years of teaching) still demonstrates the reality in school classrooms. This is also in line with the findings of the TALIS report on the teaching approaches used in school classrooms (TALIS, 2014).

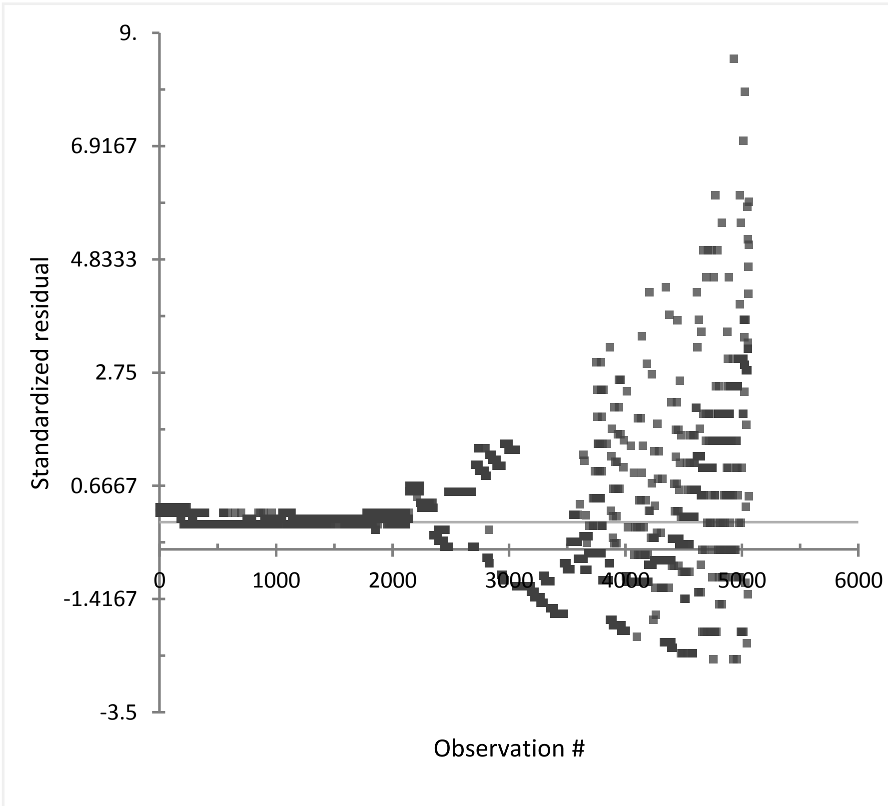
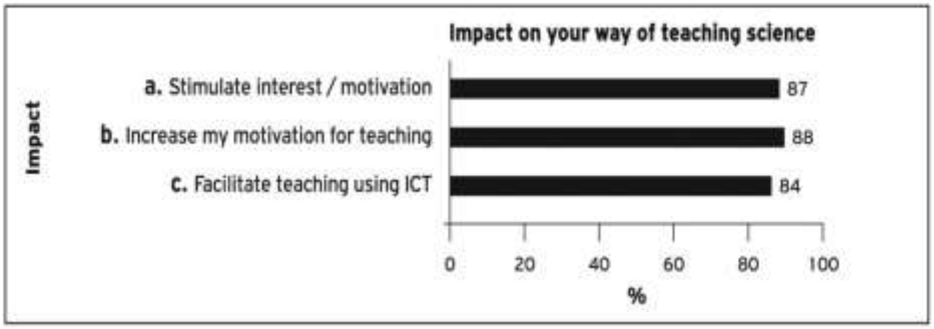


Figure 2. The graph demonstrates a large portion of teachers as having rather limited experienced in implementing inquiry-based techniques. As the time in service increases, the distribution widens, too: the difference between the years of teaching and the years of implementation of inquiry techniques varies significantly. With such a large-scale survey a background study is necessary in order to demonstrate the potential of the proposed professional development scheme for teachers with many years of experience.

We analyzed the anticipated pre-event and right after an event) and the medium-term (a few months after the event) impact of the training events. Participating teachers on average had an average of some 11 years of teaching experience and rated their experience in the implementation of inquiry-based approaches as rather limited to about 2 years on average (see Figure 1). As expected, our sample demonstrates a behavior that is far from optimal (the amount of time that the inquiry approach is implemented throughout the years of teaching) and still demonstrates the reality in school classrooms. This is also in line with the European-wide survey on teaching approaches used in school classrooms, where inquiry- and project-based approaches are reported as applied on rather limited occasions (TALIS, 2014). Figures 1 and 2 provide an integrated view of the profile of the teachers who participated in the study. Such background work is crucial to demonstrate the real impact of the innovative PD approaches: Teachers with significant teaching experience who have not implemented inquiry in their classrooms seem convinced – by the PD programs – of the potential impact of inquiry on their teaching and on students learning and attitudes towards STEM.

PATHWAY was oriented towards improving school science education by updating teachers' methodologies, so that classroom teaching is improved in terms of transferable knowledge, skills and competences. As our approach supported the use of inquiry-based teaching and ready-to-implement classroom strategies, another important aspect was innovation and updating of teaching and learning strategies based on the thorough incorporation of ICT, so that the full potential of ICT in education is realized. On the other hand, to measure the success of intensive projects involves the efforts of hundreds of training experts and thousands of trainee teachers.

The data analysis demonstrated an increase of the teachers' knowledge base due to participation as well as in the individual attitude level towards implementation of these methodologies and the spread of the practices among peers. The possibility to take home practical and usable class-materials supported a commitment to implement the action plans developed during the events. Consequently, the existing curricula apparently offer space for interventions with well-prepared action plans localized in the school and suited to classroom needs.



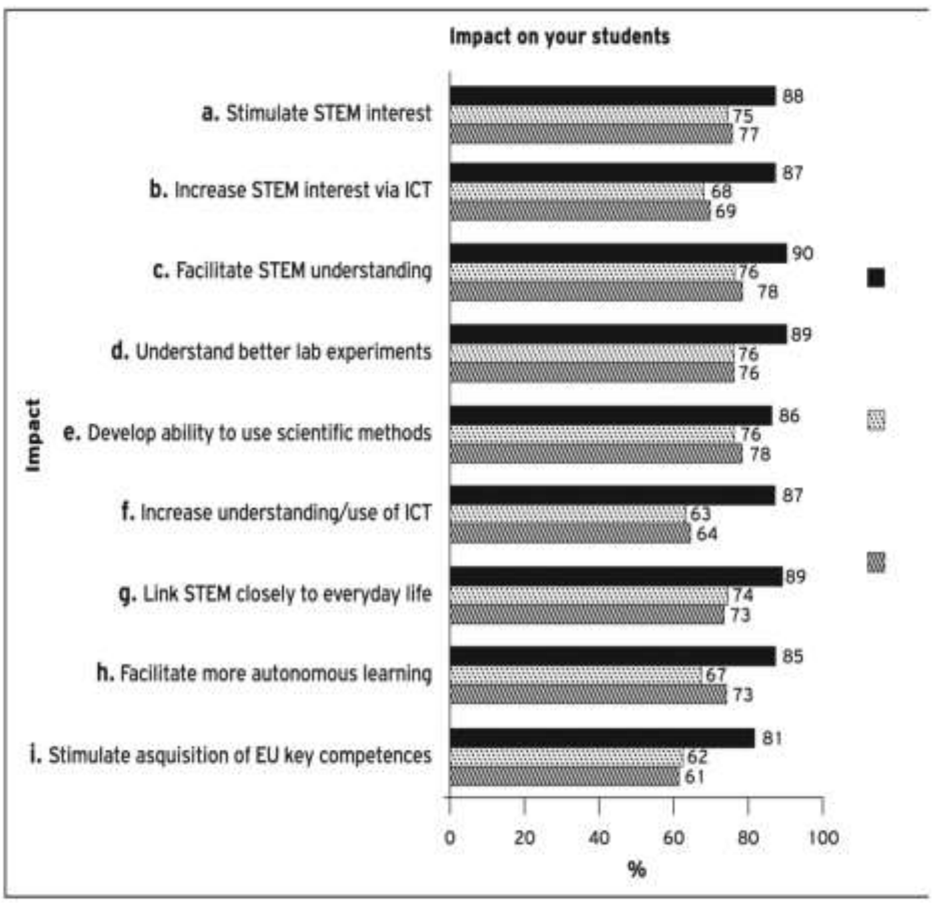


Figure 3. (upper: A) Impact of the PATHWAY professional development activities on teachers' every day practices. (lower: B) Impact on students (according to their teachers) in the framework of training activities that focus on school-based implementation (black), on activities that connect schools and informal learning places (e.g. science centers and museums) (dotted grey) and on activities that connect schools and scientific research (hatched grey).

In all cases, the data demonstrate that the proposed approach has a significant impact on their way of teaching. According to teachers' responses, the approach has managed to provide all the necessary tools required for such a change to happen in everyday practice. The most important finding was that in all cases the training was shown effective and the approach was adopted by a significant number of respondents (more than 80%). Furthermore, the impact estimation of the implementation of inquiry demonstrated a substantial impact. Figure 3 portrays outcomes of all three categories' training activities (school-based activities, activities connecting schools and science centers and museums, activities connecting school science with scientific research). Although the impact is very high on school-based activities, the data demonstrate a significant impact also for places where inquiry approaches supposedly are the norm (such as for instance museums, science centers).

4. Discussion & Conclusion

At the level of the teachers, four things may occur: (i) teachers need to become aware of individual weaknesses in classroom practices and thus need support for necessary improvements. As for a deeper change in motivation, more is needed than simply changing material incentives: a shared sense of purpose, and above all, a collective belief in their common ability is required. Individual teachers need to gain an understanding of particular best practices (for instance, through demonstration of such practices in authentic settings). (ii) Individual teachers take leadership for practitioner-led change and thus make their peers aware to fully realize the potential of resource based learning. All potential fears and negative preconceptions need consideration and, for instance, coaching in classroom practice, designing effective professional development programs, and enabling teachers to learn from each other. (iii) Consequently, effective training on inquiry-based methods constitutes a major paradigm shift for teachers to acquire new skills, abandon long-standing practices and move away from their professional "comfort zone". (iv) Finally, assisting behavioral change, that is, supporting teachers, beyond training, to adapt a new culture and philosophy.

The PATHWAY project was intended to promote inquiry-based teaching and learning, to provide a basis for establishing opportunities for inquiry-based science education. The empirical data clearly show a reasonable effect on the participating teacher community. The program seems to allow young students to think and act as scientists do, to employ inquiry instead of collecting unrelated factual knowledge. Quite different to other three-year projects, PATHWAY additionally assured its continuation within the European Science Education Academy (ESEA). This newly established institution continues the principles of our three-year project by offering: (i) guidelines for the introduction of inquiry-based approaches in school practice within European, disseminating methods and exemplary cases of effective inquiry in classrooms, extending professional development programs, supporting the adoption of inquiry-based teaching. (ii) organizing effective teachers' preparation programs by demonstrating ways to reduce the constraints presented by teachers and school organization. (iii) organizing European-wide training opportunities in summer schools to promote inquiry-based education. (iv) intervening with policy makers and curriculum developers for the effective integration of inquiry by delivering sets of guidelines to further explore and exploit its unique benefits. (v) last but not least, extending web-based repositories with relevant materials. In short, ESEA is supposed to continue the vision of PATHWAY independently of funding cycles.

Acknowledgement

We thank all students and teachers involved in our study who contributed our data as well as A. Gras-Velázquez (EUN) for supervising the project's data collection: The European School Network (EUN), the network of the EU member states' Ministries of Education, acted as a partner of PATHWAY, a European initiative with 25 institutions from 16 countries (FP7-Science-in-Society-2010-1, THEME SiS-2010-2-2.1-1; 266624). Any opinions, findings, conclusions, or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the European Commission.

References

Alberts, B. (2009). Redefining Science Education. *Science, 323*, 427. https://doi.org/10.1126 /science.1170933

American Association for the Advancement of Science (AAAS). (1993). *Benchmarks for science literacy*. New York: Oxford University Press.

Anderson, R.D. (2002). Reforming Science Teaching: What Research says about Inquiry. *Journal of Science Teacher Education, 13*(1), 1-12. https://doi.org/10.1023/A:1015171124982

Barrow, L.H. (2006). A Brief History of Inquiry: From Dewey to Standards. *Journal of Science Teacher Education, 17*, 265-278. https://doi.org/10.1007/s10972-006-9008-5

Bereiter, C. (2002). *Education and mind in the knowledge age.* Erlbaum Associates.

Burris, J. (2012). It's the teacher. *Science, 335*, 146. https://doi.org/10.1126/science.1218159

Bybee, R.W. (1997). *Achieving scientific literacy: From purposes to practices.* Portsmouth, NH: Heinemann Press.

Bybee, R. (Ed.). (2002). *Learning science and the science of learning.* Arlington, VA: NSTA Press. https://doi.org/10.2505/9780873552080

Collins, A. (1995). National science education standards in the United States: A Process and a product. *Studies in Science Education*, *26*, 7-37. https://doi.org/10.1002/(SICI)1098-2736(199809)35:7<711::AID-TEA3>3.0.CO;2-O

Conradty, C. & Bogner, F.X. (2012). Knowledge presented in Concept Maps: Correlations with conventional cognitive knowledge tests. *Educational Studies, 38*(3), 341-354. https://doi.org/10.1080 /03055698.2011.643100

Dewey, J. (1910). *How we think*. Boston, MA: D. C. Heath & Co. https://doi.org/10.1037/10903-000

Donovan, S. & J. Bransford. (Eds.). (2005). *How students learn: Science in the classroom.* Washington, DC: National Acad. Press. https://doi.org/10.17226/11102

Driver, R., Squires, A., Rushworth, P. & Wood-Robinson, V. (1994). *Making sense of secondary science. Research into children's ideas.* New York: Routledge. https://doi.org/10.1187/cbe.05-02-0068

Falik, O., Eylon, B. & Rosenfeld, S. (2008). Motivating teachers to enact Free-Choice PBL in Science and Technology (PBLSAT): Effects of a professional development model. *Journal of Science Teacher Education. 19*, 565-591. https://doi.org/10.1007/s10972-008-9113-8

Franke, G., Scharfenberg, F.-J. & Bogner, F.X. (2013). Investigation of Students' Alternative Conceptions of Terms and Processes of Gene Technology, *International Scholarly Research Network Education*. https://doi.org/10.1155/2013/741807

Fremerey, C. & Bogner, FX. (2015). Learning about Drinking Water: How important are the three dimensions of knowledge that can change individual behaviour? *Education Sciences, 4*(4), 213-228. https://doi.org/10.3390/educsci4040213

Garrison, D. R. & Kanuka, H. (2004). Blended learning: Uncovering its transformative potential in higher education. *The Internet and Higher Education, 7,* 95-105. https://doi.org/10.1016/j.iheduc.2004.02.001

Gilbert, J. K. & Pope, M. L. (1986). Small group discussions about conceptions in science. *Research in Science & Technological Education, 4*(1), 61-76. https://doi.org/10.1080/0263514860040107

Goldschmidt, M.& Bogner, F.X. (2016). Learning about genetic engineering in an outreach laboratory: Influence of motivation and gender on students' cognitive achievement. *International Journal of Science Education Part B, 6*(2), 166-187. (2016). https://doi.org/10.1080/21548455.2015.1031293

Goldschmidt, M., Scharfenberg, F.-J. & Bogner, F.X. (2016). Instructional efficiency of different discussion approaches in an outreach laboratory: Teacher-guided versus student-centered. *Journal of Educational Research, 109*(1), 27-36. https://doi.org/10.1080/00220671.2014.917601

Gurria, A. (2012). *PISA 2012 Result in Focus. What 15-year-olds know and what they can do with what they know.* Paris, OECD.

Harlen W. (2010). *Principles and big ideas of science education*. Association for Science Education, Hatfield, UK.

Hattie, J. (2009). *Visible learning*. Routledge, London, New York.

Hodson, D. (1993). Re-thinking old ways: Towards a more critical approach to practical work in school science. *Studies in Science Education, 22,* 85-142. https://doi.org/10.1080/03057269308560022

Kali, Y. & Linn, M. (2009). *Designing Coherent Science Education: Implications from Curriculum, Instruction, and Policy*. Teachers College Press.

Keselman, A. (2003). Supporting inquiry learning by promoting normative understanding of multivariable causality. *Journal of Research in Science Teaching, 40*, 898–921. https://doi.org/10.1002/tea.10115

Kuhn, D. (2005). *Education for thinking*. Cambridge, MA: Harvard University Press.

Langheinrich, J. & Bogner, F.X. (2016). Computer-related self-concept: The impact on cognitive achievement. *Studies in Educational Evaluation, 50,* 46-52. https://doi.org10.1016/j.stueduc

Lakoff, G. & Johnson, M. (1999). *Philosophy in the flesh. The embodied mind and its challenge to western thought.* New York: Basic Books.

Linn, M. C. (2000). Designing the knowledge integration environment. *International Journal of Science Education, 22*(8), 781–796. https://doi.org/10.1080/095006900412275

Meissner, B. & Bogner, F.X. (2012). Science Teaching based on Cognitive Load Theory: Engaged Students, but Cognitive Deficiencies. *Studies in Educational Evaluation, 38*, 127-134. https://doi.org/10.1016/j.stueduc.2012.10.002

Michaels, S., Shouse A. & Schweingruber, H. (2008). *Ready, set, science: Putting research to work in K-8 science classrooms.* Washington, DC: National Academies Press.

Minner, D.D., Levy, A.J. & Century, J. (2010). Inquiry-based science instruction – what is it and does it matter? Results from a research synthesis years 1984-2002. *Journal of Research in Science Teaching, 47*(4), 474-496. https://doi.org/10.1002/tea.20347

Mullis, I., Martin, M.O., Foy, P. & Arora A. (2011). *TIMSS 2011 International Results in Mathematics.* Chestnut Hill, MA, USA.

National Research Council (NRC). (2011). *A framework for K-12 science education: Practices, crosscutting concepts, and core ideas.* Washington, DC: National Academies Press. https://doi.org/10.17226/13165

NGSS Lead States (2013). *Next generation science standards: For states by states.* Washington, DC: The National Academies Press. https://doi.org/10.17226/18290

Osborne, J. & Dillon, J. (2008). *Science Education in Europe: Critical Reflections*. A report to the Nuffield Foundation.

Pilkington, R. M. (2004). Developing discussion for learning. *Journal of Computer Assisted Learning, 20*, 161–164. https://doi.org/10.1111/j.1365-2729.2004.00080.x

PISA (2000). *Knowledge and Skills for Life. First Results from the OECD Programme for International Student Assessment (PISA).* OECD, Paris.

Randler, C. & Bogner, F.X. (2009). Efficacy of two different instructional methods involving complex ecological content. *International Journal of Science and Mathematics Education, 7*(2), 315-337. https://doi.org/10.1007/s10763-007-9117-4

Renkl, A., Mandl, H. & Gruber, H. (1996). Inert Knowledge: Analyses and remedies. *Educational Psychologist, 31*(2), 115–121. https://doi.org/10.1207/s15326985ep3102_3

Rocard, M., Csermely, P., Jorde, D., Lenzen, D. & Walberg-Henriksson, H. (2007). *Science Education Now: a Renewed Pedagogy for the Future of Europe*. Brussels: European Commission.

Schaal, S. & Bogner, F.X. (2005). Human visual perception. Learning at workstations. *Journal of Biological Education, 40*(1), 32-37. https://doi.org/10.1080/00219266.2005.9656006

Scharfenberg, F.-J. & Bogner F.X. (2010). Instructional Efficiency of Changing Cognitive Load in an Out-of-School Laboratory. *International Journal of Science Education, 32*(6), 829-844. https://doi.org/10.1080/09500690902948862

Scharfenberg, F.-J. & Bogner F.X. (2011). A new two-step approach for hands-on teaching of gene technology: Effects on students' activities during experimentation in an outreach gene-technology lab. *Research in Science Education, 41*(4), 505-523. https://doi.org/10.1007/s11165-010-9177-2

Scharfenberg, F.-J. & Bogner, F.X. (2013a). Instructional efficiency of tutoring in an outreach gene-technology laboratory. *Research in Science Education, 43*(3), 1267-1288. https://doi.org/10.1007/s11165-012-9309-y

Scharfenberg, F.-J. & Bogner, F.X. (2013b). Teaching gene technology in an outreach lab: Students' assigned cognitive load clusters and the clusters' relationships to learner characteristics, laboratory variables, and cognitive achievement. *Research in Science Education, 43*(1), 141-161. https://doi.org/10.1007/s11165-011-9251-4

Scharfenberg, F.-J. & Bogner, F.X. (2016). A New Role-Change Approach in Pre-service Teacher Education for Developing Pedagogical Content Knowledge in the Context of a Student Outreach Lab. *Research in Science Education, 46*(5), 743–766. https://doi.org/10.1007/s11165-015-9478-6

Schmid, S. & Bogner, F.X. (2015). Effects of Students' Effort Scores in a Structured Inquiry Unit on Long-Term Recall Abilities of Content Knowledge. *Education Research International,* (Article ID 826734). https://doi.org/10.1155/2015/826734

Schwab, J. (1966). *The teaching of science.* Cambridge, MA: Harvard University Press.

Schwab, J.J. (1960). Enquiry, the science teacher, and the educator. *Science Teacher*, 6-11.

Schwarz, C. V. & White, B. Y. (2005). Metamodeling knowledge: Developing students' understanding of scientific modeling. *Cognition and Instruction, 23*(2), 165–205. https://doi.org/10.1207 /s1532690xci2302_1

Shamos, M. (1995). *The Myth of Scientific Literacy*. Rutgers Univ. Press.

Shulman, A. & Valcarcel, J. (2012). Scientific knowledge suppresses but does not explain earlier intuitions. *Cognition, 124,* 209-215. https://doi.org/10.1016/j.cognition.2012.04.005

Sotiriou, S. & Bogner F.X. (2011). Inspiring Science Learning: Designing the Science Classroom of the Future. *Advanced Science Letters, 4*, 3304–3309. https://doi.org/10.1166/asl.2011.2039

Sotiriou, S. & Bogner F.X. (2008). Visualize the Invisible: Augmented Reality as an Innovative Science Education Scheme. *Advanced Science Letters, 1*, 114–128. https://doi.org/10.1166/asl.2008.012

Sotiriou, S., Bogner, F.X. & Neofotistos, G. (2011). Quantitative analysis of the usage of the COSMOS science education portal. *Journal of Science and Technology Education, 20*, 333-346. https://doi.org/10.1007/s10956-010-9256-1

TALIS (2014). TALIS 2013 Results An International Perspective on Teaching and Learning. https://doi.org/10.1787/9789264196261

Valanides, N. & Angeli, C. (2008). Distributed cognition in a sixth-grade classroom: an attempt to overcome alternative conceptions about light and color. *Journal of Research on Technology in Education, 40*, 309–336. https://doi.org/10.1080/15391523.2008.10782510

White, B.Y. & Frederiksen, J. R. (1998). Inquiry, modeling, and metacognition: Making science accessible to all students. *Cognition and Instruction*, *16*, 3–118. https://doi.org/10.12691/education-4-9-10

Wu, H.K., Lee, S.W.Y., Chang, H.Y. & Liang, J.C. (2013). Current status, opportunities and challenges of augmented reality in education. *Computers & Education, 62*, 41-49. https://doi.org/10.1016 /j.compedu.2012.10.024