International Refereed Journal of Engineering and Science (IRJES)
ISSN (Online) 2319-183X, (Print) 2319-1821
Volume 6, Issue 6 (June 2017), PP.22-27

Experimentation in science, engineering, and education

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Abstract: Experimentation is used differently in science, engineering, and science education. The aim of many science fairs is to encourage young talent in scientific inquiry. Based on 57 interviews with participants of a German youth science fair, this article points out typical students' conceptions about the procedure and the purpose of experimentation. The analysis of the interview data revealed that the derived concepts firstly depend on each other and secondly reflect the differences in the way of thinking and working between scientists and engineers. Since experiences with experimentation provide the basis for learning and thus for the conceptual knowledge about science, we conclude that it is essential, for science education, to distinguish the engineer's and the scientist's point of view and to implement more authentic inquiry in science lessons at school.
Keywords: conceptual change, experiments, inquiry-based learning, science education

I. INTRODUCTION

Experimentation is crucial for engineering, natural and computer science, as well as for science education. The aim of this article is to draw attention to the difference in understanding experimentation within these fields and to point out the difficulties for science education generated by that difference. Engineering and science complement and inspire each other. Research in natural science provides the scientific basis for implementing technical ideas, for inventing new technologies, for thinking and working as an engineer. Specific technical applications and more precise devices enable scientists to measure, capture, and understand nature more and more profoundly. In a sense, engineering and science thus form a symbiosis. As a consequence of this merging, a problem of teaching experimentation as one of the most important scientific inquiry methods occurs [1]. We therefore assumed that students have problems to distinguish experimentation between engineering and science in terms of procedure and purpose.

Scientific experimentation is defined as an orderly procedure carried out with the goal of testing a hypothesis by systematically manipulating the conditions of the observed processes or variables to be measured [2, 3]. This scientific procedure generally, but not necessarily, contains the following steps: (1) formulating a research question, (2) generating a theory-based hypothesis, (3) designing the experiment, (4) conducting the experiment and collecting data, (5) preparing and evaluating the data, (6) interpretation and discussion of the results and their conclusions, and (7) communication of findings. Of course, we do not claim that this sequence is the one and only scientific method. However, there is a broad consensus nationally and internationally within the science education community on the need to convey such a basic understanding of scientific thinking and working [4, 5].

At school, experiments function in a variety of ways such as motivating students, testing hypotheses, or illustrating concepts [6]. Here, the teacher generally knows the outcome of the experiment, whereas the result of a research experiment is unknown. However, the key element in classroom instruction is whether the teacher has communicated to students what the expected result should be. We therefore distinguish the typical "school experiment" with explicit instructions and known results from the "research experiment", which is part of the scientific process described above.

A scientist asks a question to nature and works to get an answer to this question. Based on a theory, the scientist's aim is to test a hypothesis. Whereas for scientists, the purpose of experimentation is knowledge gain ("open-ended"), engineers usually carry out experiments for technical improvements ("intended"). To fulfil the requirements of a task, engineers want to achieve a specific effect. Since they have different goals, scientists and engineers may additionally use different procedures for experimentation. During everyday life, most people think and act more like an engineer than a scientist, because they daily use things, especially technical devices as a result of social and technological change, as a means to an end and thus want to achieve a certain effect, too.

Experimentation is also the core element of many science fairs. In order to retrace scientific inquiry, students can compete with each other by presenting their own small research projects. In many countries, science fairs have a long tradition to expand normal classroom teaching [7]. On the one hand, to support and challenge students individually, and on the other hand, to enhance lessons and also to build the external profile of the school. Researchers have investigated various aspects of science competitions in the context of science education. Some of them focused on different factors that lead to successful participation [8]. Gender effects among participants were found in some motivational respects such as self-concept of own competence and social role attributions [9] or in the choice of science field [10]. Task-oriented science olympiads reach other types of students than project-centred science fairs [11].

In Germany, the most popular youth science fair with over 10,000 students participating annually is "*Jugend forscht*" (which literally translates to "Youth Does Research"). The non-profit organisation behind this competition sees the education and encouragement of young adults in mathematics, computer science, natural science, and engineering as a key task to provide a basis for future research and innovation in our society. The main goal of the competition is to encourage young talent in scientific thinking and working. The competition follows a periodic annual structure (November 30th: closing date; February: regional competitions; March/April: state competitions; May: national competition). For their submitted projects, students are free to work alone or in small groups of 2-3. Scientific experimentation is most commonly at the centre of the projects. Participants assign their projects to seven different subjects: biology, chemistry, physics, earth sciences, mathematics or computer science, engineering, and working environment. On the competition days, the students present their projects to a jury. This presentation in front of the project poster is usually a mixture of a short talk and a discussion among experts.

In our nationwide study about *Jugend forscht*, we analysed learning processes about experimentation and the nature of science (NOS) triggered or supported by a science fair. We used both oral interviews (n = 57) and software-based questionnaires (n = 1,070; pre-, post-, follow-up-test). Some of these data are already published [12].

The science fair, *Jugend forscht*, seems to be a suitable environment for the investigation of student conceptions about experimentation within the fields of science and engineering, because of the defined objectives, the focus on experimentation, and the project-centred approach of this competition. To this end, the present article addresses the two questions: Which conceptions exist about experimentation among the participating students in terms of procedure and purpose? Do these conceptions reflect differences in the way of thinking between scientists and engineers? Considering the possible influence of previous experiences with experiments at school and during everyday life, we assumed that students are used to the engineer's point of view and mainly understand experiments to achieve a desired effect. However, the awareness of the difference between experimentation in science and engineering is seen as an essential basis for an advanced conceptual knowledge about scientific inquiry and natural science in general.

II. THEORY AND METHODOLOGY

In a moderate constructivist sense, learners need to learn actively [13]. Additionally, we understand learning by means of a revised conceptual change approach [14, 15], which considers a situated perspective [16]. We see students as individual learners who construct their knowledge in an active and self-regulated process on the basis of existing conceptions. These conceptions derived from everyday experiences can be beneficial or obstructive for learning [17]. Thus, we understand conceptual changes as reconstructions of conceptions [18], where conceptions can be further developed, changed, or newly formed, depending on the context and the individual.

To obtain students' conceptions about experimentation, we used guided interviews as a qualitative research tool also applying the method of the retrospective query on learning processes (Paul, Lederman, & Groß, 2016). A total of 57 individual interviews were conducted during regional competition days. For that purpose, all 872 participating students of five different regional competitions in Bavaria and Thuringia were contacted beforehand, concerning their willingness to be interviewed. From the 263 positive responses, 57 volunteering students from 10-18 years were randomly chosen for the interviews to produce an approximately equal distribution of interviewees with respect to location, age, gender, and the topic of their work with an emphasis on natural sciences (average age: 14,9 ± 2,6 years; 28 males, 29 females; topics: 19 biology, 18 chemistry, 14 physics, 2 engineering, 2 geoscience, 2 mathematics and computer science). All personalized data were made anonymous.

An interview lasted for about 30 minutes and started in a time frame of 30-60 minutes after the visit of the competition jury. We used a structured guideline to align the 57 interviews for reproducibility. Two different researchers conducted the interviews. The interview guideline integrates two methodological approaches: firstly problem-oriented, open and half-open questions to collect the current conceptions about scientific experimentation and secondly the retrospective query on the individual learning process. Several basic questions were drawn from validated questionnaires [19, 20, 21], from which subsequent questions were developed. The interviews were captured using a voice recorder. The interrelationship between questions and answers was validated by three different researchers based on qualitative content analysis (in line with [22, 23]). In addition, an internal triangulation process with similar questions on the same issue was integrated into the guideline. For reliability, coding and interpretation of students' statements were analysed by two researchers working independently. The findings of both were then reconciled if necessary. The organized statements of the students were summarized into tables, where the conceptions mentioned retrospectively were differentiated from the current conceptions. By comparing these conceptions, we were able to construct the learning process on the basis of the detected conceptual changes or the additionally accrued concepts. In order to reconstruct the sequences of the learning processes, the concepts identified were linked with each other step by step according to the conceptual changes made by the subjects.

III. RESULTS

Students' statements about experimentation

In order to represent typical students' experiences and their associated statements about experimentation, three characteristic examples are quoted. Alicia, a 12-year-old, experiences experiments in school differently from the ones at *Jugend forscht* (see Table 1, example 1). During the experiments in school, she gets detailed instruction how to carry out the experiment or is only a spectator, where the teacher presents experiments as a demonstration for the entire class. At *Jugend forscht*, Alicia not only takes matters in her own hands, she also does so without explicit guidelines from the teaching staff and without written instructions. 54 of the 57 students questioned usually carry out experiments at school as part of a group, or with a partner following written instructions.

The 16-year-old Peter tells about his individual learning process (see Table 1, example 2). Formerly, Peter saw experiments as entertaining, they were rather spectacular ("flash"). His additional experience was to use experiments for trying various ways in order to construct something with a specific aim. Both conceptions have in common, that a certain effect should be achieved via experiments. During the course of the science fair, it became clear to him that the result of a scientific experiment is previously unknown and may be different from the expectation. Through experiments, you can "prove things" or you can "get new findings" to answer a question. With this, Peter is an example of the learning process from the conception that experiments serve as entertainment or to achieve a desired effect, towards the conception that the purpose of scientific experimentation lies in knowledge production.

Talking to other participants, the 15-year-old Dan figured out that distinct types of experimentation exist (see Table 1, example 3). He noticed other students who pursued to construct a specific device and tried to improve its properties. Thus, he differentiates between experiments serving the purpose of a technical improvement and those, carried out by "scientists", serving the purpose of knowledge gain. The possibility of alternative appropriate conceptions of the purpose of experimentation was mentioned by 8 participants interviewed at the science fair. The three students, Alicia, Peter, and Dan represent typical conceptions of experimentation found in this study.

Table 1: Three representative student statements from the 57 individual interviews conducted about experimentation (translated extracts from the original transcripts, key passages are marked as shaded text, the time display is given in hours:minutes:seconds).

1. Experiments in School and at *Jugend forscht*	
00:10:38	*Interviewer:* "How do you experience experiments in school?"
00:10:42	*Alicia (12 years-old):* "Sometimes we do experiments in biology. Last time we observed the germination of cress seeds. We had a detailed instruction how to do so and worked together in groups of 3 or 4. But in most cases, when we had experiments, we simply watched the teacher while he was doing the experiment. (...)"
00:11:36	*Interviewer:* "And how do you see experimentation at *Jugend forscht*?"
00:11:41	*Alicia:* "Differently. We did not have a guideline and did everything alone. (…) Without concrete instruction, but on our own and freely."
2. Learning processes for the purpose of experimentation	
00:25:23	*Interviewer:* "What did you know about experimentation before you did your *Jugend forscht* assignment?"
00:25:29	*Peter (16 years-old):* "Before, I thought experiments are just entertaining, maybe a nice flash for example. (...) Or you want to construct something and you try different ways, waiting for that what you want. (…)"
00:27:26	*Interviewer:* "Earlier on, you said that you learned something through the science fair. What did you mean? What did you learn about science?"
00:27:37	*Peter:* "When you do real experiments, you don't know what comes out. Experiments can run differently than expected. And you have to accept your result, also if it is different. (…) You can prove things by yourself, and sometimes you get new findings. You ask a question and you can find something. And there is still a lot to explore."
3. Difference between engineering and science	
00:18:11	*Interviewer:* "Have you talked to other participants?"
00:18:16	*Dan (15 years-old):* "Yes, there was another group. They tried to construct a small rocket, just with a plastic bottle, water, and effervescent tablets. They did a great job. (…) They used experiments for technical improvements. We had, more or less, a scientific question. (…) As a scientist, you carry out experiments to expand your knowledge."

Concepts about the procedure and the purpose of experimentation

Participants in the science fair had a comprehensive understanding of experimentation, and thus they referred to very different features. We know from our previous research that learning processes may occur within five distinct subdomains of learning [12]. These subdomains are procedure, purpose, material, control, and time. The related main concepts are the following: experimentation needs a step-by-step *procedure*; experiments have a *purpose*; experiments need *materials*; an experiment requires a *control*; experimentation takes *time*.

Focusing on procedure and purpose, we found 9 different concepts regarding experimentation (Fig. 1 and 2). The concepts #1-5 are assigned to procedure, the concepts #6-9 pertain to purpose. Several of the interviewees reported that their conceptions changed during the course of the science fair. Some of these changes reflect replacements of previous concepts with new concepts. Alternatively, new concepts arose in addition to the previous concepts or merely modified or complemented the existing concepts. We linked the concepts identified with each other according to the conceptual changes made by the students and derived typical pathways and steps of learning (Fig. 1 and 2). A comparison of the steps of learning shown in Fig. 1 with our understanding of the scientific approach during experimentation (cf. introduction) reveals that cumulative learning has taken place. The interview data showed that, when participants expressed a higher concept, this always implied knowledge of the other aspects below in the sense of a sequence during experimentation (QHERD, Fig. 1). With the final concept (# 5), the students approached the scientifically usual view of the procedure of experimentation, including formulating a research question (Q).

We furthermore compared the two subdomains of learning with each other and found a strong correlation between their concepts. If a participant held the concept #8 ("Experiments serve the purpose of a technical improvement") or below within the subdomain purpose, he never revealed the concept #5 ("Finding a question is part of experimentation"). Typically, concept #8 was linked to concept #3 ("Experimentation means trying out variations"). If a student reached the concept #5 and alluded to the purpose of experiments anyhow, he always attained the concept #9 ("Experiments serve the purpose of knowledge gain"). Characteristically, concept #7 ("Experiments are conducive to illustration and comprehension") accompanied concept #2 ("For experiments, detailed instruction is needed"). In summary, the two subdomains procedure and purpose obviously depend on each other.

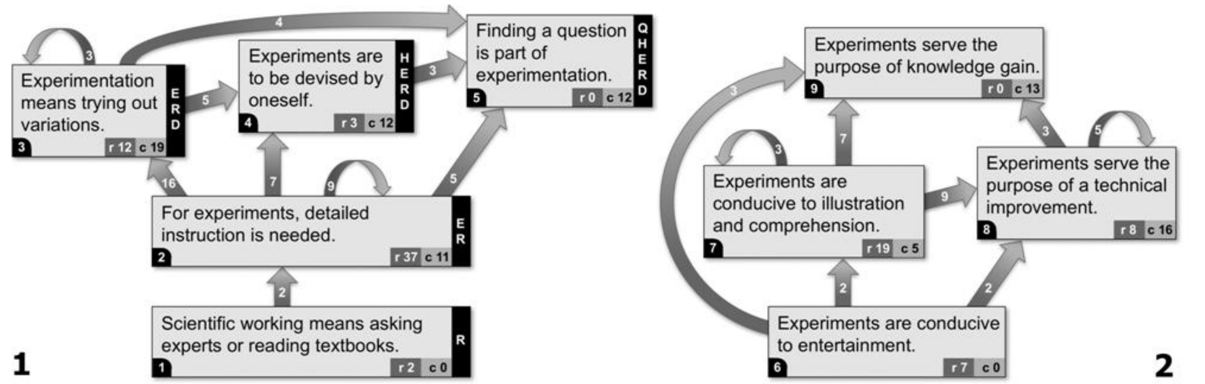

Figure 1, 2: Concepts and steps of learning about the procedure (Fig. 1, n = 54) and the purpose (Fig. 2, n = 34) of experimentation. Single concepts are numbered consecutively (1-9, at the bottom left within each box). Learning processes are performed according to arrows by a specific number of participants (numbers within arrows). Returning arrows imply that concepts did not change. At the bottom right within each box, dark grey cells show the number of participants who held the respective concept before the science fair (r, retrospective view). The light grey cells show the number of participants who revealed the respective concept on the day of the competition (c, current concept, during the interview). White letters in Fig. 1 correspond to the scientific procedure of experimentation: Q = question; H = hypothesis; E = execution of experiment, collecting data; R = results, evaluating the data; D = discussion and conclusion.

IV. DISCUSSION AND CONCLUSION

Above, we showed the various concepts about the procedure and the purpose of experimentation found in this study. The Figures 1 and 2 illustrate typical steps of learning experimentation. Two main reasons for conceptual developments could be detected [12]: Firstly, within the framework of the science fair, the participating students have the opportunity to work using methodology similar to the commonly accepted scientific path of knowledge. Secondly, due to communication processes during the science fair, a purposive reflection of their own project is promoted.

The most vital new finding presented in this article is that the concepts of the procedure and the purpose of experimentation are strongly linked to each other. Learning experimentation is often described as a straight line stepped process with different levels of complexity. Our findings reveal that concepts develop rather according to a cross-linked map. This leads to our second research question: Do the students' conceptions about experimentation reflect differences in the way of thinking between scientists and engineers? Yes, they do. The linked concepts # 3 and 8 perfectly correspond to the "engineer's model of thinking", since an engineer typically wants to produce a desired and interesting phenomenon by testing variations [1]. An engineer heeds those variables and results that seem to be relevant to achieve the goal, which often is a technical improvement. Besides, the linked concepts # 5 and 9 cogently reflect the "scientist's model of thinking". A scientist usually intends to understand cause-effect relationships to extend knowledge by designing an experiment suitable to answer a specific question. Based on a theory, a scientist systematically tests hypotheses under controlled conditions. Epistemologically, scientific theories cannot be verified but can only be disproved [24]. Of course, the two ways of thinking are not rated here, rather than analysed in the sense of science education. Anyhow, students are predominantly used to the engineer's point of view (16 of 34 students represented the concept #8; 19 of 54 students referred to concept #3), although only 4 of 57 participants had assigned their projects to the subjects engineering, mathematics or computer science. The projects of the other 53 participants belong to natural science subjects. In addition, we found that concept #8 never accompanies concept #5. Thinking and acting as an engineer differs from scientific inquiry. Some students contrasted these different approaches and were aware of the differences (Table 1, examples 2 and 3). In order to enable a deeper comprehension of science, a question must be in the foreground. If this concept was developed (concept #5), also the sense of science was better understood (concept #9).

The influence of experience on learning and development is beyond any doubt [25]. Here, the previous experiences about experimentation provide the basis for the conceptual knowledge about science. In the media and at school, experiments often serve the purpose of entertainment (concept #6). The TV host or teacher demonstrates an experiment as a spectacular event. At school, experiments are mostly used for illustration and comprehension (#7). For this, a detailed instruction is needed, at least if the students carry out the experiment. During everyday life (cf. introduction) and even at a science fair, which is supposed to encourage students in scientific thinking and working, experimentation is experienced as it serves to achieve a specific effect or goal, e.g. a technical improvement (#8). The experience of authentic inquiry, including a research question and a hypothesis, conveys the insight that scientific experimentation serves the purpose of knowledge gain (#9). The existence or the manner of the question particularly makes the difference between the engineer's and the scientist's point of view. For science education, there are consequently two important steps, which should be taken before an experiment is carried out: Firstly, a problem should be recognized and limited in order to formulate a question. Secondly, after devising a hypothesis, the experiment should be planned with respect to the question and to theory [24].

In conclusion, it is essential for science education, both for teachers and for students, to distinguish the two different ways of thinking and working during experimentation, on the one hand as an engineer, and on the other hand as a scientist. Together with a stronger anchoring of authentic inquiry in science lessons at school, this will smooth the way for a fundamental understanding of science.

ACKNOWLEDGEMENTS

We thank the foundation *Jugend forscht* e.V. for cooperation during our research project, particularly Dr. Sven Baszio (managing director), Sigrid Müller-Balhorn (head of competition management), and Stefan Gagel (head of one regional competition).

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