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Designing digital fabrication learning environments for Bildung: Implications from ten years of physical computing workshops

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ABSTRACT

The first programmable bricks appeared about 30 years ago, and attributed to constructionist hands-on learning. With the upcoming of FabLab initiatives and the maker movement, learning activities with digital fabrication technologies have now gained importance and spread over the world. Educational concepts that contribute not only to acquisition of skills but also to *Bildung* (i.e. deep and sustainable learning) are demanded more than ever.

For more than a decade, we have designed, conducted and evaluated constructionist learning environments for digital fabrication with physical computing material focusing on children. In the course of our research, we identified core ideas to facilitate *Bildung* that are summarized as *be-greifbarkeit* (being 'graspable'), *imagineering* and *self-efficacy*. In this article, we elucidate these principles and show how they occur and can be facilitated in learning environments for digital fabrication with programmable construction kits. By further applying the ideas to novel production technologies, we identify challenges and give implications for integrated educational and technology designs for young people that take into account the unique qualities of digital fabrication technologies for Bildung.

1. Introduction

About 30 years ago, the first programmable bricks empowered children to construct interactive, digitally enhanced devices on their own. These construction kits were based on the idea of learning about abstract concepts by designing concrete objects. Rooted in constructivist theories [1,2], the theory of constructionism [3] emphasizes learning by constructing not only mental models, but also personally meaningful artefacts. With the rise of the maker movement [4] and new digital fabrication technologies that are accessible to many, digital fabrication activities have gained importance for education and are entering into schools and spare time activities. We define 'digital fabrication' as the making of physical digitally enhanced artefacts as well as the making of materialized objects by means of digital models. Following this definition, technologies for digital fabrication comprise of physical computing technologies as well as digital production machines for printing three-dimensional objects and for cutting, shaping or milling material. While digital fabrication in educational contexts has gained popularity during recent years and is often linked to the history of constructionism [5], we still see a lack of educational concepts that take into account the qualities of digital fabrication technologies and build upon the existing body of research on digital fabrication with programmable construction kits. Of special importance are concepts that not only focus on skill development, but also contribute to *Bildung* (i.e. deep, sustainable learning) about digital technologies.

Sticking with the German term Bildung we emphasize its meaning that goes back to Wilhelm von Humboldt: Bildung may translate into a kind of education that means "learning-to-be" instead of "learning about" [6]. It refers to a development of the individual personality in interaction with the material and social environment [7]. This encompasses complex and deep learning, not just the acquirement of skills for a specific purpose. It does not address the ability to repeatedly act according to fixed rules, instead it means that a development of the person as a whole and (in the sense of Piaget's understanding) an alteration of mental models takes place as a change of self in interaction with the environment. Sustainable learning means that different situations can continuously be handled where the abstract model is applied appropriately [8]. In the modern Western and quickly changing information based world, this is the kind of learning more and more asked for (e.g., [9]).

For more than a decade, we have researched the implementation of digital fabrication workshops for children under the name

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of *TechKreativ*. With these learning environments we orientate towards an understanding of digital media as *Bildungsmedien*. This means that not only a didactical concept is important, but also the medium with its technology has to be designed accordingly. Calling the computer a Bildungsmedium refers to its inherent representation of important concepts of today's society and its digital culture. As Murray puts it: "The digital medium is as much a pattern of thinking and perceiving as it is a pattern of making things. We are drawn to this medium because we need it to understand the world and our place in it" Murray [10, p. 11]. It was Sherry Turkle, who first called the computer an "evocative object" back in the 1980s [11, p. 17]. Digital fabrication environments are exciting learning environments with evocative material that allow for learning experiences with digital media in many dimensions. They open many opportunities for social and participatory learning, whereas schools, as institutions of industrial society, remain behind or make it at least difficult to offer innovative potential for new forms of learning [12].

TechKreativ primarily focuses on designing and evaluating appropriate learning environments with programmable construction kits (Section 3), but during the last couple of years we have also included digital production technologies (Section 4). During the course of our ten years of research with TechKreativ, we have identified core ideas that are essential for Bildung about digital technology and that are inherent in our learning environments: *be-greifbarkeit*, *imagineering* and *self-efficacy*. With be-greifbarkeit (similar to the double meaning of 'graspable') we refer to making connections between virtual and physical worlds and between the abstract and the concrete. Imagineering means to invent and create yet unknown products that relate to personal life worlds. Self-efficacy is related to empowerment and means that the individual perceives herself as acting sovereignly (with digital media) in a digitalized world, and gains the confidence to not only live in, but contribute to it. In this paper, we explain and amplify these ideas in more detail (Section 3) and show how physical computing construction kits and educational concepts (exemplified by our TechKreativ workshops) can contribute to Bildung. We discuss their applicability to new digital fabrication technologies such as 3D printers and laser cutters and demand new educational designs for learning environments aiming at Bildung.

1.1. Methodology

The three core ideas have been extracted in iterative cycles of evaluating and redesigning TechKreativ learning environments since 2004. In total, we conducted approximately 40 workshops with programmable construction kits (including Lego RCX,[1] Crickets,[2] Arduino and Arduino LilyPad[3]) following the general TechKreativ concept illustrated below. Besides the programmable boards, sensors and actuators, different crafting materials and common tools were provided depending on the topic of the workshop. To program the hardware, the participants used visual programming environments (usually *Amici*[4]). Most workshops lasted between three to five days full time and took place at the FabLab of the University the authors work at. Workshops were offered as spare time activities during holidays or as project work for diverse school classes. Children were usually aged between 9 and 15 years and of both gender. On average, 15 children participated in a workshop guided by two or three tutors.

Embedded into research projects with differing foci, the workshops were evaluated from slightly altering perspectives, e.g. gender issues [13], attitude towards technology [14], and subject formation [15]. Eight workshops were evaluated in-depth using only qualitative methods (semi-structured interviews and/or observation or contextual inquiry), nine workshops were evaluated using only quantitative methods (questionnaires), and another eight were evaluated using triangulations of both methods.

While based on the general idea of constructionism, the scope of our workshops is strongly related to realizing the idea of Bildung through the digital medium. Its objectives are not just directed to the acquisition of knowledge or skills, but at stimulating all of a person's personality in interchange with the outer world, acting with objects. From the beginning, the TechKreativ concept was constantly refined based on evaluation results from previous workshops in iterative cycles of design and research. Over time, we identified essential core ideas. They have served as basis for further workshop designs, including new fabrication technologies. The core ideas be-greifbarkeit, imagineering and self-efficacy are specifically connected to Bildung with digital media, as we will describe.

1.2. Overview

In the next section, we introduce the concepts of programmable construction kits and constructionism and typical learning environments. In section three, we introduce our TechKreativ learning environment with a *vignette* and introduce the core ideas *be-greifbarkeit, imagineering* and *self-efficacy* and their relation to Bildung. In Section 4, we exemplify how we implement the core ideas and discuss potentials and challenges for transferring them to learning environments with different technologies for digital fabrication. We conclude by showing demands for future research on designing integrated learning environments to contribute to Bildung.

2. Background: programmable construction kits

The first programmable bricks informed by constructionist learning were designed in the 1980s [16,17]. These microcontroller 'bricks' can be equipped with sensors and actuators and programmed. They enable children to design and build ubiquitous computing objects, and through this explore concepts of programming and computer technology. Among the first programmable construction kits were the Handy Cricket board [16] and the related Lego Mindstorms RCX [18].

The concept of programmable construction kits is rooted in the learning theory of constructionism by Seymour Papert [3]. Constructionism was initially inspired by Piagetian learning theories, but does not limit construction activity to constructing internal mental structures. Instead, learners are not only actively constructing knowledge rather abstractly in their minds, but act as designers of concrete objects [19]. These objects can be seen as external representation of mental concepts and help to reflect the construction process. The object becomes an "object-to-think-with" [3, p. 11]. It evokes from the learner to think 'with' and about it, and by that to get in touch with new concepts and underlying ideas. Constructing an object is an iterative activity. Through externalizing ideas as an object, errors or inadequacies in thinking become explicit. Consequently, mistakes are even necessary for learning, providing for reflection about one's mental concept.

With current Maker trends and open hardware movements, opportunities for hands-on learning with physical computing have increased. The availability of low-cost open source technologies, such as the Arduino, has contributed to this. Arduino has not been designed primarily for children's learning and poses challenges

1 https://education.lego.com/en-us/preschool-and-school/secondary/11plus-mindstorms-education/rcx.

2 http://handyboard.com/cricket/.

3 http://arduino.cc.

4 http://dimeb.de/eduwear/amici.