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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 summarised 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.

Key words

Digital fabrication; constructionism; Bildung; education; physical computing.

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 (Piaget & Inhelder, 1969; Vygotsky, 1971), the theory of constructionism (Papert, 1980) emphasises learning by constructing not only mental models, but also personally meaningful artefacts. With the rise of the maker movement (Anderson, 2012) 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 materialised 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 (Martinez & Stager, 2013), 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 emphasise 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" (Fischer & Wolf, 2014). It refers to a development of the individual personality in interaction with the material and social environment (Humboldt, 1793). 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 (Sterling, 2001). In the modern Western and quickly changing information based world, this is the kind of learning more and more asked for (e.g., Hjorth & Iversen, 2014).

For more than a decade, we have researched the implementation of digital fabrication workshops for children under the name 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 2003, p. 11). It was Sherry Turkle, who first called the computer an "evocative object" back in the 1980s (Turkle, 1984, 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 (Schelhowe, 2013).

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 digitalised 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.

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

[1] https://education.lego.com/en-us/preschool-and-school/secondary/11plus-mindstorms-education/rcx
[2] http://handyboard.com/cricket/

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 (Reichel & Wiesner-Steiner, 2006), attitude towards technology (Katterfeldt, Dittert & Schelhowe, 2009), and subject formation (Walter-Hermann, Büching & Schelhowe, 2012). 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 realising 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.

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 the fourth section, 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 (Resnick, Martin, Sargent, & Silverman, 1996; Blikstein, 2013a). 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 (Resnick et al., 1996) and the related Lego Mindstorms RCX (McNerney, 2004).

The concept of programmable construction kits is rooted in the learning theory of constructionism by Seymour Papert (1980). Constructionism was initially inspired by Piagetian learning theories, but does not limit construction activity to constructing internal mental structures. Instead, learners

[3] http://arduino.cc
[4] http://dimeb.de/eduwear/amici

are not only actively constructing knowledge rather abstractly in their minds, but act as designers of concrete objects (Harel & Papert, 1991). 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" (Papert, 1980, 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 externalising 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 e.g. in terms of usability (Blikstein, 2013a) and transparency level (Blikstein & Sipitakiat, 2011). But in general, construction kits with Arduino share similar principles and are nowadays widely employed as programmable bricks in diverse educational settings covering arts as well as STEM (Buechley, Eisenberg, Catchen & Crockett, 2008; Beginner's Mind Collective, 2012; Manylabs kits[5]).

In educational contexts it is not sufficient to just build technology. Concepts on how to invite young people to become creators of their own artefacts are needed (Papert, 1984). The technology needs to be embedded in learning environments that support the qualities of the material and allow for learning in a 'constructionist' way. Accordingly, constructionist learning environments have been created. For instance, so-called computer clubhouses[6] have spread around the globe. These are open locations where youngsters can come in to work with construction kits on projects that "build on their own interests" (Rusk, Resnick & Cooke, 2009, p. 20). In "an environment of respect and trust" (ibidem, p. 24) they can get help if they want but they can also work autonomously. Besides computer clubhouses, an ever-growing number of FabLab initiatives have emerged around the globe. They offer similar learning environments for young people—of whom the most prominent is FabLab@school[7]. Arduino (and similar programmable boards) are often reported to be used in interdisciplinary learning environments with constructionist or project-based learning approaches. Especially combining physical computing with creative arts and crafting projects is popular. Goals are mostly to motivate more students to engage in computer science and STEM subjects, or to foster computer literacy (DuMont, 2012; Qiu, Buechley, Baafi, & Dubow, 2013; Kafai et al., 2014; Giannakos, Jaccheri, & Proto, 2013; Blikstein, 2013).

3 Core ideas for digital fabrication learning environments for Bildung

The Case of TechKreativ

With the TechKreativ workshops we have created an approach for integrated learning environments with a focus on Bildung. The environment integrates (1) physical tools, materials and a programming environment, (2) a didactical workshop concept, (3) a context (addressing a motivational topic, inviting parents for presentation), (4) a physical environment and (5) staff (with educational, technological and scientific background for planning, tutoring, evaluating). We illustrate the concept of TechKreativ with a vignette.

> 12 girls and boys are participating in a three-day TechKreativ workshop during their summer holiday at the authors' University FabLab, guided by three tutors. They have been

[5] https://www.manylabs.org
[6] http://www.computerclubhouse.org/
[7] https://tltl.stanford.edu/project/fablabschool

> attracted by the workshop announcement to become inventors of gadgets to explore their movements when doing sports. At the first day of the workshop, all participants go out to an exercise area to try out different sports activities, including kicking a ball. Luca and Leon (both 11 years old) like to play soccer. Peter (12 years old) jumps in and wants to show that he is able to shoot it really hard. Luca and Leon disagree that this is shooting hard. Back in the workshop room the boys get to know the Arduino materials available to construct a sports measurement device. They see flat pressure sensors that indicate how much pressure is put on it. They come up with the idea to put two of these on a shoe to prove to Peter that his shot is not that hard. The boys decide to construct a device that measures the intensity of a shot.
>
> Within the next two and a half days, the three boys construct and program their soccer shoe based on an old shoe brought from home. They attach the sensors—one to the instep and the other one to the inner side of the foot—a LilyPad Arduino at the heel, and LEDs in green, yellow and red that provide feedback on the intensity of the shot. They experiment with several positions for the sensors to get appropriate measurements and write a program with the programming environment Amici that shows the values the sensors deliver. That way, they find out how hard they actually shoot—especially compared to each other—and define thresholds between strong, moderate and soft shots. A strong shot is indicated in red, a moderate one in yellow and a soft one in green light. While constructing they repeatedly try it out in the room and outside. During that process they realise that their initial conception of shooting power as a fixed value is wrong. While one of them first states that "hard is hard" the other two boys convince him that it needs to be adjusted to individual players. This includes the individual position of the sensors as well as the thresholds of soft, moderate and hard. Based on their findings, they re-program their device again and again until they are satisfied and decorate it. At the end of the workshop they present their device in front of a public, where they explain and show how their device works.

This *vignette* illustrates one of the main ideas behind TechKreativ: linking technology construction to a specific non-technological topic, e.g. sports. Examples of previous topics are: 'magic', 'spooking', 'smart fashion', 'wear & move', 'smart dance', 'senses & sensors', 'moves make music'. Topics are chosen by the research team to address diverse interests and motivations and to build a (design) space for creativity. Figure 1 shows samples of project outcomes (including the soccer shoe). Kits have been developed for these purposes, i.e. the EduWear kit (Schelhowe, Katterfeldt, Dittert & Reichel, 2012) and the TechSportiv kit (Dittert, 2014). Although individual workshops have alternating topics, they all follow the same sequence: approaching ideas according to a general topic, getting to know the physical computing materials, making ideas concrete by taking into account the limitations and opportunities of the material, iteratively designing, constructing and programming artefacts and finally presenting the projects to an audience (for further details, see Schelhowe et al., 2012).

Figure 1: Soccer shoe (upper left), thief-proof handbag (left), piano glove (centre), two magic creatures (right).

In the following, we exemplify how and why a learning environment with computational construction kits like TechKreativ can foster be-greifbarkeit, imagineering and self-efficacy and by that contribute to Bildung in today's digital world.

Be-Greifbarkeit: Abstract models become 'graspable'

Through the materialisation of digital models, digital fabrication activities have the general potential to provide interactions that make the underlying models *be-greifbar*. The German verb 'begreifen' is similar to the English word 'to grasp' and comprises two different meanings: on the one hand, 'greifen' means to grab something, to touch and to feel it haptically, with your hands or your whole body; on the other hand 'begreifen' stands for understanding or making sense of something, with your mind. In this double meaning, the noun 'Begreifbarkeit' refers to understanding by grabbing, and grabbing to understand. It underlines the connection between body and mind or acting and thinking. The spelling "be-greifbarkeit" stands for the connection to technology as opposed to classical graspable materials like wooden blocks.

For be-greifbarkeit, tangibility and body interaction have to come together with formalisation activities. Both sides are present as physical and virtual representations in the digital medium itself. Computer based media allow on the one hand very concrete action and experience, whereas representing on the other hand a climax of abstraction (Papert & Turkle, 1991). Thus, digital media provide appropriate access to realise what a lot of outstanding educators from Fröbel to Montessori to Dewey have stressed: "The question of the integration of mind-body in action is the most practical of all questions we can ask of our civilization" (Dewey, 1984, p. 29).

In our vignette, the soccer shoe represents the children's mental concepts on shots in soccer: What is hard, moderate and soft? Which are the significant parts of the foot for these shots? The children transfer these aspects into a formal language and into the design of the shoe: How does it measure the intensity? How does it create feedback? How do I translate this behaviour into program code?

From a constructionist perspective, the children create "objects-to-think-with" that can be regarded as external representation of mental concepts. Kafai & Resnick define "[...] some artifact—be it a robot, a poem, a sand castle or a computer program—which they can reflect upon and share with others" (Kafai & Resnick, 1996, p. 1) as such an object. The object-to-think-with is at the core of the learning process and be-greifbarkeit.

But be-greifbarkeit is not only reached by having an object-to-think-with. It also requires a concise design of learning environment and material that render their inner algorithmic models 'graspable' to the learner. Furthermore, not every tangible technology implies be-greifbarkeit as such. It needs to allow for iterative explorations of concepts. Programmable construction kits incorporate be-greifbarkeit very well: constructing and programming an artefact using a construction kit requires to align a mental concept with a tangible shape. Due to the nature of programming and circuiting, iterative cycles of redesigning and debugging are needed. The tangible object that is created serves to verify the mental concept and triggers reflection. Ackermann points out the importance of alternating phases of immersion and reflection for constructionist learning. The iterative process of constructing an artefact allows for a „[...] dance between diving-in and stepping-out [...]" (Ackermann, 1996, p. 28) and hence for on-going reflections. Dittert (2014) shows that this occurs when children construct artefacts for sports in TechKreativ learning environments. Not only do the boys in our vignette think through their formerly implicit movement, but they also need to abstract from it and formalise and quantise. By testing and iterating the artefact, Luca, Leon and Peter compare how it works and how they expect it to work. They draw connections between the formalisation and their perception of the actual movement. Thus, they experience fundamental concepts of sensing and computing—the digital medium itself is being 'grasped'. By iteratively constructing and testing their sports device, they 'do the dance' between bodily performance and mental engagement of what has happened and reflect on their movement and its implementation. By materialising mental models and allowing for reflection in an iterative construction process involving body and mind, deep and sustainable learning, the perception and change of one's self can occur. Since these principles are central to be-greifbarkeit, we infer that be-greifbarkeit is one fundamental principle for learning environments in the context of digital fabrication.

Imagineering: Creative approaches to technology

Following constructionist theory, people learn through designing—building, programming, making artefacts. Having objects-to-think-with contributes to learning with a designerly approach to making. The object under construction becomes an artefact to reflect own ideas and to engage in a reflective conversation with the material (Schön, 1983). Kafai & Resnick (1996) identify "construction of meaning" (ibidem, p.4) as a core process of design theory as well as constructionist theory. The product outcome itself isn't in focus, but the reflective process of designing it. Another essential element of designing as well as of constructionist learning is *imagination* (Folkmann, 2013; Resnick, 2007; Schelhowe, 2007). Imagination refers to creativity and inventiveness—core activities in constructionist learning processes. But it also connotes to imaginary ideas that are not yet externalised and materialised—ideas that are personally meaningful to people and that they bring in from their life world. In our vignette, Luca, Leon and Peter are immersed in their sports and envision different opportunities they could design for. They create an idea that strongly links to their personal life world and implement it with technology. Therefore, we coin our second core principle *imagineering*. The word—also used by Disney[8]—implies for us the creative personally meaningful side of the construction activity, but also the concrete part of physically implementing the imaginations, and the relation between both.

[8] https://disneyimaginations.com/about-imaginations/about-imagineering/

Programmable bricks as design material provide “rich connections” to the user’s world (Resnick et al. 1996, p. 444): they encourage connections to their life world and thus can support imagineering. Especially smart textiles and other universal technical components allow for a variety of connections ranging from arts and crafts to STEM. Current physical computing construction kits support and incorporate these principles. For instance, LilyPad Arduino or MaKey-MaKey[9] are made for connecting with crafting material and support their usage for diverse topics, which are usually not related to technology. To support the affordances of physical computing material further, the TechKreativ workshop concept fosters the principle of imagineering by linking technology to creative approaches—but imagination always comes first. At the sports workshop described in the vignette, we first went out to do different kinds of sports and explore what everyone would like to improve about their movements. Only afterwards the children were confronted with the technology and its limitations. We further choose generic gender-sensitive topics that link to children’s imagination and to personally meaningful problems. Problems do not necessarily need to be real-world problems, but can also relate to personal agency and self-expression. In the workshop described in our vignette, for example, the boys chose their favourite sport and Peter’s personal issue for investigation although they had tried out other sports outside, too. This was also true for the other participants so that we revised the design of the ‘imaginary’ activity phase and focused on participants’ favourite sports for the next workshops (Dittert, 2015).

Imagineering is interrelated with the idea of be-greifbarkeit. Be-greifbarkeit stresses the dualism of body and mind, whereas imagineering stands for the reciprocal process of referring to personal meaningful ideas and implementing them using technology. Integrated learning environments like TechKreativ open up interdisciplinary fields to which a diverse range of learners can connect without being intimidated and limited by technology in the beginning. Children do not build robotics to (only) learn about robotics, but transfer and discover principles of computational ubiquitous technology from and back to everyday life. In the case of the vignette, Luca, Leon and Peter linked their passion for playing soccer to the technical implementation of their shoe and gained new insights about their movements in return. Deep learning is involved in such a process, as the learners themselves with their interests are the starting point of the construction activity. They link their interests to the generalised and abstract concept of tangible technology and programmability that is implemented in the artefact. This process provides way for Bildung to happen as an alternated connection of the individual to the world.

Self-efficacy and relating oneself to technology

In a constructionist understanding of education, the experience of self-efficacy is the basis for personal development. The individual develops his and her personality and capacity according to own activity, power and experience to be able to change the environment, i.e. the surrounding objects and processes. Self-efficacy refers to the personal belief of having “the power to produce desired effects” (Bandura, 2003, p. 87) and has a positive effect on motivation and performance and thus personal development (Bandura, 1997). Aiming at *self-efficacy* is the third core idea incorporated in learning with programmable construction kits that contributes to the idea of Bildung.

Self-efficacy is a learning outcome often reported in the context of digital fabrication. For instance, Qiu et al. (2013) report on increase in self-efficacy after smart textile workshop that follows a similar philosophy like TechKreativ with “learning by doing”, “encouraging early success” and “supporting multiple learning styles” (Qiu et al. 2013, p. 22) and similar material. Children claimed that they felt more capable in using technology and programming than before the workshop.

[9] http://www.makeymakey.com

Ornelas, Blikstein & Calderon (2014) report on changes in self-efficacy and technological awareness of high school students who took part in a comprehensive digital fabrication after-school program.

Programmable bricks are evocative and give children “the power to create and to control” (Resnick et al., 1996, p. 444) with a low threshold. In our vignette, the children experience that they are able to invent and construct a novel artefact with technology they had previously encountered as consumers. They can be in control of the artefact and adjust it to their personal needs. But they can only achieve this in a constant negotiation with the environmental conditions and the capacities and limitations of the technology that may require adaptations and revisions of their initial ideas. Peter, Leon and Luca had to adapt their idea by using a limited number of sensors and measuring points, and only few LEDs to indicate the results of their shooting. They experienced that they are able to invent and implement a novel personal device, but that the technology imposes challenges and follows rules. E.g., they had to identify an optimal sensor placement at the shoe where to hit the ball.

Changes in children's attitudes towards technology and programming were also shown in our EduWear project where children created interactive garments. The evaluation results proved that a smart textile construction kit embedded in the EduWear/TechKreativ[10] workshop concept lead to a feeling of empowerment as active designers, perceived self-efficacy and attitude towards technology and handicraft. The construction of wearables resulted in a more 'realistic' and adequate attitude in terms of being able to program, especially with boys, while the girls’ confidence increased in respect of their technological competences. Further, smart textile construction kits and the EduWear/TechKreativ concept proved suitable to relate to the children’s everyday life world (Katterfeldt et al., 2009; unpublished evaluation report). Zorn (2008) conducted interviews with children and adults who had been involved in various construction processes of digital media, including TechKreativ workshops. She explored the interviewee’s perception of the construction activities and how thereby educational processes evolved, comparing TechKreativ construction activities with activities where technology was rather used for digital content or graphical design. Zorn’s evaluation results showed that the TechKreativ construction activities hold potential for the constructors to reflect on the relations between themselves and their own impact on the world. Participants described themselves as creators of their environment, instead of consumers and persons affected by technological developments. They were reflecting on the relation between themselves and their own liveliness, on the one hand, and the digital artefact as a kind of actor in the interactive process (their co-construction activities) on the other. This all means that during their activities, participants gain new insights into the reciprocal action between their own activities and the digital culture surrounding them. They perceive themselves as producers and put themselves in new relation to this world and its technology—an essential characteristic contributing to Bildung.

4 Designing learning environments with digital fabrication technologies

In the following we exemplify how we implement learning environments that facilitate be-greifbarkeit, imagineering and self-efficacy, and discuss how the core ideas can be transferred to learning environments using other digital fabrication technologies. Because digital *production* technologies have qualities appropriate for constructionist learning activities (Martinez & Stager, 2013) and Bildung (Schelhowe, 2013), we include reflections on our experiences from eight 3D printing and laser cutting workshops with children that followed the TechKreativ didactical concept and sequence (see above), and were conceptualised and tutored by staff members with experience in previous TechKreativ workshops.

[10] The EduWear concept implemented the same principles like TechKreativ, but used only smart textile material.

Be-greifbarkeit: Facilitate iterations with objects-to-think-with

Be-greifbarkeit stands for bringing body, mind, abstract model and concrete interface together by means of tangible digital media to allow for reflection as a prerequisite for deep and sustainable learning. Regarding learning environments for digital fabrication, we recommend supporting be-greifbarkeit by allowing for iterative construction of objects-to-think-with to reflect on the relation between perception, digital models and implementation involving body and mind. For designing learning environments, this means that children get space and time to create products that are durable enough to be tried out 'in action' and not only construct functional prototypes that are unstable or remain on a miniature level. Accordingly, we provide complementary materials that support iterations but also allow for reliable artefacts (e.g., by soldering connections once they are approved instead of only using breadboards). We embed the construction activity into a suitable overall generic topic that evokes relations between body, mind and abstract model.

Programmable kits support short iterative cycles very well. Due to their programmability and interactivity, links between abstract coding and concrete physical action can be experienced immediately. Wearable kits like TechSportiv seem ideal means to help learners to reflect on themselves and their actions. However, in workshops with laser cutting and 3D printing technologies we observed that these technologies restrict iterative work with objects-to-think-with. The digital software model alone lacks graspable object-to-think-with qualities, which led us to provide additionally prototyping material that may (partly) compensate for this absence, e.g. pen and paper for sketches (laser cutting) (Dittert, Katterfeldt & Wilske, 2014) or modelling clay (3D printing) showed potential for creating 'objects-to-think-with' that make the inner thoughts explicit in alternation with the software model.

For programming (or modelling) artefacts we prefer software tools like Amici that are not black boxes but reveal the abstract model behind the digital medium. Many programming environments for construction kits render principles of computing visible and provide a low threshold for beginners to formalise their ideas. However, custom drag-and-drop software tools for 2D and 3D modelling conceal the formalisation of objects or patterns. Underlying principles of the digital medium remain hidden and the process of drawing connections between the formal description and the actual object is not supported (see also Zeising, Katterfeldt & Schelhowe, 2013). In order to promote be-greifbarkeit we are developing scenarios with Processing[11] where the code behind objects is accessed while designing (Dittert et al., 2014).

Imagineering: Provide richer connections to life world

Imagineering connotes the reciprocal process of referring to personal meaningful ideas, or imaginations, and implementing these using technology for digital fabrication. Individual interests are linked to abstract concepts and support meaningful learning experiences to be transferred back into the children's life worlds again. We recommend providing ways for imagineering in learning environments for digital fabrication by linking to problems not only from the real world, but also from personal imagination, to allow for the linking of personal realities with technological concepts 'at hand'.

To implement imagineering, we frame a gender-neutral, age-appropriate topic that allows for multiple connections for each workshop. At the workshop, we start with an imagination phase about the topic. We found it especially fruitful in terms of creative projects to begin with idea creation before introducing any technology and made this an essential part of the TechKreativ concept. Thus, the children first explore the general workshop topic by imaginary journeys,

[11] http://www.processing.org

brainstorming, bodystorming or other creativity techniques. We don't show examples of implemented artefacts and technology (if we do, they are very generic ones) before or during the imagination phase because this was found to influence ideas and project outcomes significantly. Imagineering also requires taking back the implementation into life. Not necessarily physically, but by presenting it to family and friends, and by having time and space to try it out. During the construction phase, we provide complementary (crafting) material that supports the topic (e.g., sweatbands for sports to attach the electronics). Children can also bring their own object they want to pimp up (like in the soccer shoe example). We found that interdisciplinary topics and the children's projects and experiences can benefit from having one tutor with expertise in the field. E.g., we worked with a fashion designer, a magician, a dance educator, and a sports teacher.

The rather long history of programmable bricks led to many application areas, ranging from robotics (Junior et al., 2013) to scientific investigations (Resnick, Berg & Eisenberg, 2000), to fashion (Buechley et al., 2008). Such construction kits have the unique property of enabling users to invent and create 'intelligent' artefacts and "autonomous creatures" (Resnick et al., 1996, p. 447) that are interactive and have an effect on their environment. This supports the implementation of imagineering very well. Digital production machines have different qualities: they aim more at designing (real-world) *products* than addressing real-world and imaginary *interactive processes*. While programmable bricks create rich connections to young people's life worlds, we see a challenge for digital production activities. For instance, we observed that 3D printed and laser cut objects were often influenced by images that already exist (e.g. printing soccer club logo), instead of inventing and designing new imaginary objects. On the other hand, materials are low-cost so that children can take home everything they produced. More scenarios supporting imagineering with digital production activities are needed (e.g., see Eisenberg (2013)'s visions). Imagineering might also be supported by a fruitful combination of construction kits with digital production.

Self-efficacy: Black boxes and mastering of technology

Self-efficacy refers to being in control of the digital medium, but also setting oneself and ones capabilities in relation to the technology and its limitations. It is strongly related and may partly result from implementing be-greifbarkeit and imagineering. In the context of learning environments for digital fabrication, we recommend aiming for self-efficacy through the process of becoming producers, not only consumers, and also by assessing oneself in relation to environment and technology.

Programmable kits designed for education allow children to be in control of their artefact. At the same time, they are also limited in functionality, follow their own rules (due to their digitality) and require setting oneself, one's personal ideas and goals into relation to the technology. Concerning the TechKreativ concept, we support this additionally with a programming environment that children can master on their own very soon without copying/pasting unknown code segments. We assist children to find solutions for their projects themselves within their own frame of capabilities and within the scope of the workshop technology and tools, but try not to interfere actively in the implementation (although their might be more elegant or advanced solutions).

Again, when transferring this core idea to learning environments with digital production technologies, we face challenges. Before an object can be printed in 3D or laser cut, it usually requires adjustment of the digital model in a separate software and configuring and setting up the machine. In our current experience, children still cannot do all steps on their own but need technical assistance by a tutor. The machine remains partly a black box. This may result in less perception of control—not feeling that "*I* can make it myself"—and less self-efficacy compared to working with programmable construction kits. Thus, educational design of the production machines and software is required that carefully considers black boxing of the underlying technology and children's mastery of tools (e.g. tools by Gross & Eisenberg (2007)). Novel machines promise to make the printing process less error-prone (e.g., Cube printer[12], Printeer[13]). Whether and how they contribute to educational designs in terms of self-efficacy and further Bildung needs to be investigated.

5 Conclusion

In this article, we presented the three core ideas be-greifbarkeit, imagineering and self-efficacy as essential requirements for learning environments for digital fabrication that facilitate Bildung. The ideas build on principles rooted in constructionist learning, but have been enhanced by our research in physical computing workshops with children during the last ten years. In addition to constructionism, we highlight the interaction between body and mind, creativity and technology and self and environment. The core ideas highlight the unique properties of digital fabrication, especially programmable construction kits, and associated learning environments that allow to relate one's life world to modern technology, reflecting on the digital medium through the unique opportunity of digital fabrication to become graspable, perceiving oneself as producer considering own capabilities and by that offer deep, sustainable learning beyond mere skill acquisition.

We showed how these ideas are implemented in TechKreativ learning environments for digital fabrication with programmable construction kits, but also identified challenges in transferring them to learning environments with novel digital fabrication technologies. The three principles and our implications can guide educators, researchers and designers of future learning environments for digital fabrication for Bildung.

Following our results, we demand more concepts for sustainable learning with digital production technologies to contribute to Bildung in today's digital world. Designers of learning environments for digital fabrication should be aware of the unique qualities of the fabrication technologies to be used. Sustainable learning with and about production machines may require different concepts than those with physical computing technologies. It needs to be acknowledged that the umbrella term 'digital fabrication' comprises diverse technologies that demand differentiated educational designs. Machines and tools for digital production need educational designs, too, and may target different aspects of Bildung. On the conceptual level, more research is needed to take further learning theories into consideration and to develop appropriate concepts for digital fabrication in educational contexts. In the near future, we keep developing new learning environments for digital production taking into account our findings.

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[12] http://cubify.com/en/Cube
[13] https://www.kickstarter.com/projects/2001363001/printeer-a-3d-printer-for-kids-and-schools

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