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Learning by Doing and the Underestimated Prerequisites for Digital Design Competence

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Abstract

Maker education combines hands-on creation with the testing of artifacts. In the process, tool requirements may become apparent that remain undefined in general descriptions of digital media use. The starting point for this critical narrative review is three accounts of a plenary lecture and reports from the subsequent discussion regarding difficulties with CAD and input devices. This paper relates these experiences to research on making, digital competence, and teacher education. It distinguishes between competence frameworks and conceptual models on the one hand, and empirical studies as well as published findings from project experiences on the other. The analysis specifies requirements for modeling cubes, developing digital learning spaces, and constructing a bat detector. Digital competency frameworks already take design into account; however, their translation into task-specific learning activities and appropriate support remains an open question. For teacher education, the paper establishes a connection between teachers' own design experience, the identification of technical difficulties, and the planning of subject-specific investigations. Further studies are needed to address the frequency of such difficulties, general gains in competency, and the effectiveness of individual forms of support.

Maker Education verbindet eigene Gestaltung mit der Erprobung von Artefakten. Dabei können Werkzeuganforderungen sichtbar werden, die in allgemeinen Angaben zur digitalen Mediennutzung unbestimmt bleiben. Ausgangspunkt dieses kritischen narrativen Reviews sind drei Arrangements eines Plenarvortrags und Berichte aus der anschließenden Diskussion über Schwierigkeiten mit CAD und Eingabegeräten. Der Beitrag setzt diese Erfahrungen zur Forschung über Making, digitale Kompetenz und Lehrkräftebildung in Beziehung. Er unterscheidet Kompetenzrahmen und konzeptionelle Modelle von empirischen Untersuchungen sowie veröffentlichten Befunden von Projekterfahrungen. Die Analyse konkretisiert Anforderungen beim Modellieren von Würfeln, beim Entwickeln digitaler Lernräume und beim Herstellen eines Fledermausdetektors. Digitale Kompetenzrahmen berücksichtigen Gestaltung bereits; offen bleibt ihre Übersetzung in aufgabenspezifische Lernhandlungen und geeignete Unterstützung. Für die Lehrkräftebildung wird eine Verbindung eigener Gestaltungserfahrung mit der Diagnose technischer Schwierigkeiten und der Planung fachlicher Untersuchungen begründet. Aussagen zur Häufigkeit solcher Schwierigkeiten, zu allgemeinen Kompetenzzuwächsen und zur Wirksamkeit einzelner Hilfen erfordern weiterführende Studien.

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1. Starting Point and Research Question

Digital design requires knowledge that is rarely apparent in the everyday use of digital media. Anyone modeling an object in a CAD application must be able to interpret spatial views, coordinate inputs, and assess the consequences of individual operations. When translating this into a physical object, manufacturing requirements come into play. Maker education provides access to such activities because learners develop and test their own artifacts. This term refers to pedagogical approaches in which learners design, create, test, and modify objects or digital products themselves. What matters is not just the finished product, but the engagement with questions, errors, and decisions during the design process [9–12]. Educational goals such as creativity, problem-solving, and digital literacy [1–3] are thereby linked to concrete decisions. However, whether learners can actually make these decisions also depends on their prior experience with tools and the support they receive. The plenary presentation "Learning by Making: Fostering Future Competencies for Tomorrow's World" at the Lessons Learned VIII conference presented three teaching-and-learning arrangements from schools and teacher education programs. Children designed individual cubes using TinkerCAD, which were then 3D-printed and examined. Teacher education students developed digital learning spaces incorporating gamification elements [15]. Another project combined the construction of a bat detector (B@t Detector, www.digibats.de) with an exploration of ultrasound and species conservation. In these projects, participants were required to technically implement their own design intent and provide a subject-matter rationale for it. The projects are thus aimed at different groups: The cube project targets elementary school-aged children between 8 and 11 years old, who combine digital design with the investigation of an object they have created themselves. The digital learning spaces are developed by teacher education students as future educators; here, the technical design is complemented by a didactic assessment of the learning experience. The B@t Detector focuses on the connection between technical fabrication and scientific exploration. During the prototyping phase, the detector was initially built by adults from the fields of education and higher education. Subsequently, it was built by teacher education students for the elementary and secondary levels, and finally by children aged 8 to 11. The goal was to gradually adapt the complexity of the construction process to the target group—elementary school children.

In the subsequent discussion, participants reported difficulties with CAD software, spatial views, and coordinating the mouse and keyboard. Similar experiences were described by teacher education students and practicing teachers. These reports do not constitute a systematic survey. However, they provide an opportunity to examine a widely held assumption about digitally supported teaching: What experiences are assumed when learners are provided with a digital design tool?

This paper examines how research on maker education and digital competence describes such requirements and what implications this has for teacher education. Here, digital design competence refers, in a task-oriented sense, to the ability to realize one's own intent using digital tools, to evaluate the result, and to modify the design in a reasoned manner. The term serves to analyze the arrangements presented; it does not claim to be an independent, validated competency model. The focus is on the question of how technical prerequisites can become objects of learning, rather than remaining unrecognized assumptions when students begin working on open-ended tasks.

2. Methodology of the Review

This paper is structured as a critical narrative review. It synthesizes literature from maker education, competency research, and teacher education to address a task-oriented research question. Grant and Booth distinguish between types of reviews based on their objectives and methodological approaches [4]. The designation "narrative" in " " does not exempt the author from providing a transparent presentation of the literature base and the line of reasoning; the SANRA quality assessment tool [5] also emphasizes this. The starting point

consists of the works cited for the plenary presentation and the projects, supplemented by sources from their reference lists. This article is not based on a logged database search with documented search strings and a comprehensive selection process. Therefore, no claims can be made regarding the completeness of the current state of research or the frequency of specific findings.

The literature is categorized according to its relevance to the research question. Constructivist
artistic foundational texts explain the role of self-made artifacts. Research studies on "making" are examined in terms of which learning activities they investigate and what conclusions their design allows. Competency frameworks serve as conceptual classifications; they are not interpreted as evidence of effectiveness. The three teaching-learning arrangements specify requirements and possible consequences. One published study is available for each of the cube project and the digital learning spaces [14, 15]. The presentation of the B@t Detector is treated as a project experience; the accompanying publication is currently in the printing phase and is scheduled to appear in 2027. Additional reports can be found on the project website. Reports from the plenary discussion raise further questions but do not allow for a comparison of the competencies of children, students, and teachers. The close alignment of the literature review with the authors' own projects further limits the synthesis: While it can identify suitable explanations, but can assess competing approaches only within the scope of the works considered.

3. Maker Education as a Learning Environment

In constructivism, the creation of an artifact takes on a cognitive function. This approach is based on the assumption that knowledge is not merely acquired but is constructed through active engagement with the environment. In making, this engagement becomes tangible through a malleable, visible artifact: an idea can be tested, discussed with others, and refined based on its implementation [6,7]. The focus is also on which subsequent questions are further explored with the help of the artifact. Thus, artifacts are not created solely for the sake of the manufacturing process but serve as tools for addressing follow-up questions that build upon them. Papert, as well as Harel and Papert, describe how learners express and refine their ideas while developing products that are personally meaningful and shareable with others [6,7]. A design specifies which idea is to be implemented. The resulting artifact makes this decision verifiable and creates opportunities for discussion and modification. Blikstein applies this approach to digital fabrication [8]. A digital model can be transformed into a physical object, whose properties in turn raise questions about the design.

Maker education encompasses a variety of materials, tools, and organizational forms [9–12]. For the question addressed here, it is relevant how creative freedom, technical support, and subject-specific requirements interact. Sheridan et al. examine three makerspaces in a comparative case study, Sheridan et al. examine three makerspaces and analyze their learning processes using various data sources [10]. The design provides context-based insight into making practices. However, it does not provide experimental evidence that a specific set of equipment or type of task improves general competencies. Therefore, no conclusions regarding the impact on a school or higher-education teaching.

In open-ended design tasks, problems arise from the learners' decisions. A form chosen by the learner may prove difficult to produce; a technical obstacle may require a change in the idea. Help from others then becomes essential for continuing the work. Such processes explain why "making" is problem-solving and collaboration [10,11]. For instructional planning, it remains to be clarified which of these actions a task actually requires. A largely prescriptive set of building instructions offers different decision-making options than a design whose function and implementation must first be developed.

Bevan's review critically examines the extent to which research supports claims that "making" constitutes science education [13]. This shifts the focus from the appeal of making to the subject-specific practices in which learners engage. For the arrangements presented here,

this means explicitly planning the transition between design and investigation. In the case of the cube, the properties of the self-designed object should lead to questions about its behavior. In the case of the detector, the technical function must be linked to an explanation of ultrasound and signal detection. In the digital learning space, students must justify how the chosen design elements support the support the exploration of a subject-specific topic. These connections arise only through appropriate tasks and opportunities for discussion.

The published cube study combines the analysis of artifacts with observations and statements made by the children [14]. Design elements can thus be examined in the context of the considerations underlying them. For the present research question, this approach is insightful because it makes tool use and subject-specific thinking accessible within the concrete process. Its scope remains limited to the situations examined. A individually designed cube and a reasoned explanation document specific actions; they demonstrate neither a general increase in competence nor transfer to other tasks.

4. Competency Framework and Research Findings

"21st-century skills" do not refer to a uniformly defined set of competencies. The frameworks considered combine interdisciplinary skills with different visions of future educational requirements [1–3]. Voogt and Roblin compare international frameworks and analyze their similarities and differences [16]. For Maker Education, this implies the need to clarify the concepts of competency used. If "problem-solving" is cited as an educational goal, it must be clear what problem learners are addressing, what decisions they are making, and how the quality of their approach is to be assessed.

Assigning an observed action to a competency area is a first step in interpretation. It does not replace examination of competency development. An unusual artifact may express an independent design solution, but it may also be based on a borrowed template. Mutual assistance can broaden shared understanding or simply delegate a work step. Without information on the creation process, these interpretations remain open. General competence attributions should therefore be traced back to the documented actions and their scope should be limited.

In addition to information processing and communication, DigComp 2.2 explicitly addresses the creation of digital content and problem-solving [17]. Technical design thus already falls within a broad understanding of digital competence. DigCompEdu focuses on the professional use of digital technologies by educators [18]. These frameworks provide a language for educational goals and areas of competence. For a specific CAD task, however, these areas must be translated into observable actions: for example, changing a view, positioning an object to precise dimensions, or recognizing an inappropriate operation. The open question thus concerns the task-specific elaboration and didactic treatment of these requirements.

The works of van Laar et al., Ng, and Falloon make different contributions in this regard [19–21]. In a systematic literature review, van Laar et al. examine the relationship between 21st-century skills and digital competencies and develop a conceptual framework based on this analysis [19]. This synthesis supports the description of challenging digital activities but does not examine the introduction to CAD software.

Ng combines a multidimensional understanding of digital literacy with a study of students' use of educational media [20]. The study addresses the learning of previously unfamiliar technologies; its self-assessment data cannot be directly used to demonstrate technical performance. Caseoon develops a conceptual framework for teachers' digital competence that classifies technical skills according to professional and context-specific requirements [21]. This framework establishes a broader educational standard but does not examine the effectiveness of a "maker" program. Together, these studies allow for a more nuanced description of technical activity.

How specific tool-use routines are acquired and how they can be transferred to other design tasks remains to be empirically clarified for the arrangements discussed here.

5. Requirements in the three learning arrangements

Digital design becomes challenging as soon as an existing tool is to be used for one's own purpose. Executing a function and assessing its suitability for the design are distinct requirements. The following examples illustrate this distinction. They also differ in terms of their target groups: Elementary school students work on a subject-specific construction and investigation task; teacher education students develop a digital learning resource for their future students; while the detector project combines technical production and subject-specific exploration in successive trials involving adults, teacher education students for the primary and secondary levels, and children aged 8 to 11. They do not represent a sequential progression of increasing competence, but rather different combinations of tool use, subject-specific questions, and technical implementation.

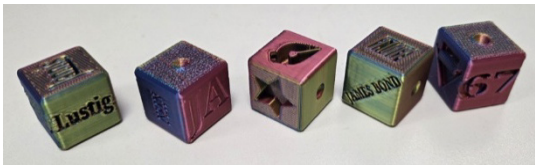


Fig. 1: In this learning activity, students use the 3D modeling software TinkerCAD to design their own cube. In the process, they creatively design the cube's faces, learn the basics of digital design, and use a 3D printer to turn their ideas into their own tangible product.

In TinkerCAD, a cube is constructed from geometric solids that are positioned, scaled, and grouped. Cutouts alter its shape. In this process, a two-dimensional on-screen view represents a three-dimensional space. Learners must distinguish whether they are changing the view or rotating the object itself. Added to this is the coordination of the pointing device, keyboard, and user interface. If a shape is in the wrong place, the first step is to determine whether its spatial position was misunderstood or whether the desired movement could not be executed technically. Both difficulties may appear similar in the finished model but require different types of assistance. A demonstration of how to use the software helps with unfamiliar input; in the case of a spatial misunderstanding, the representation must be explained or compared with a physical model.

In the digital learning spaces, the course combined the testing of tools with the development of an assessment rubric and gamified learning activities focused on species conservation. In the written reflections presented in the lecture, students described the progress they perceived, programming problems, and the significant amount of time required. These statements provide insight into their experiences, not into an independently measured increase in competence. Nevertheless, it is instructive for teaching to note what the reflections refer to: a functioning command hierarchy or the successful creation of a 3D object made a previously difficult step manageable. Whether this resulted in a didactically suitable learning activity requires a separate assessment of the subject-matter preparation and the intended learning activities.



Fig. 2: The B@t Detector converts the ultrasonic calls of bats into audible sound that humans can perceive. Three small round switches allow the functions to be turned on and off individually: Audio (audible signals), LED eye (visible signals), and Vibration (tactile signals). During the assembly process, students decide for themselves which colored switch controls which function. This allows bat calls to be perceived through different senses.

The B@t Detector broadens the perspective on technical design because it allows digital and physical work steps to be integrated. Reading

a circuit diagram, populating and soldering a circuit board, and testing a signal initially require an understanding of electrical engineering and manual skills. These activities should not be broadly labeled as digital competence. A digital component arises, for example, when a housing is modeled or a programmable component is used. For learning, the context of the individual steps is relevant: If the expected feedback does not occur, possible causes related to the power supply, the components, or the connections must be checked.

This turns troubleshooting into a verifiable technical task. Its application in a bat survey then raises questions about the significance and limitations of the perceived signal.

The scenarios demonstrate how varied the prerequisites of a design task can be. With CAD, the focus is on the connection between spatial representation and input. In the digital learning environment, a technical function must be evaluated for its didactic suitability. With the detector, errors in a physical system must be isolated. Table 1 organizes these requirements and the instructional decisions developed from them. This compilation is an analytical description of the projects; it does not constitute a validated competency model nor does it provide evidence of the effectiveness of the proposed aids.

Table 1: Requirements and Didactic Implications for the Three Teaching-Learning Arrangements

Learning arrangement	Requirements of the task	Possible Learning Activities	Implications for Teaching
3D cube with TinkerCAD	Spatial navigation, mouse and keyboard, grouping and hollowing out ("drilling"), transferring to 3D printing	Develop/draw your own symbols, form hypotheses about mass distribution, check cube results, revise the design if necessary	Combine a brief technical introduction with an open-ended design activity; jointly evaluate and reflect on the artifact and the process
Digital Learning Spaces	Tool selection, programming logic, 3D modeling, didactic simplification, design, and time management	Justify the use of gamification, integrate digital content, develop criteria, and utilize peer feedback	Do not separate technical testing from didactic reflection; allow sufficient development time; reflect on implementation in school
B@t Detector	Read the instructions, solder, check components, design the housing, interpret the signal	Narrow down errors, test functionality, examine ultrasound, deploy the device in the field	Distinguish between electrical and, where applicable, digital sub-tasks; clarify function and signal from a technical perspective

6. Tools as Part of the learning object

Tools help determine which actions a design task requires. A touchscreen, a trackpad, and a mouse offer different input options. For precise positioning in a CAD application, therefore, the specific interface, the input device, and the available functions must be taken into account. A general statement about device usage does not yet reveal which of these operations are familiar to users. The difficulties discussed in the presentation thus pertain to a task that must be analyzed within its respective technical environment.

A blanket judgment about a generation of tablet users cannot be derived from the available reports. Rather, it is necessary to examine which activities people performed using which devices. Experience with touch gestures can be helpful for one application, while another application may require unfamiliar key combinations. Whether this leads to more errors or makes the learning curve longer must be tested using comparable tasks. Similarly, differences between children, students, and teachers can only be assessed once their respective prior experiences and the conditions under which they perform the tasks have been documented.

For teaching, this results in a task-oriented assessment. Teachers must be able to recognize whether learners have not yet developed a conceptual understanding of the subject matter, misunderstand the presentation, or are unable to perform an intended step in the process. A brief task at the beginning can reveal such difficulties

Make it clear if it includes operations that will be needed later. Targeted assistance can then be provided based on this.

For example, an operational aid should explain the relevant operation and then allow students to make their own decisions again. If the teacher permanently takes over the technical execution, it remains unclear which parts of the design the students can implement on their own.

The selection of tools also affects participation. The presentation noted that schools cannot provide all children with devices suitable for certain 3D environments. This observation highlights a practical accessibility issue, the extent of which is not quantified here. However, for planning purposes, the mere availability of any digital device is not sufficient. The usability of the specific software, the suitability of the input method, and possible adaptations for different prerequisites must be clarified. Practice time and reliable support are among these access requirements.

7. Implications for Teacher Training

Teachers need experiences that allow them to jointly assess technical difficulties and subject-specific learning opportunities. Falloon's conceptual framework supports this connection between tool knowledge and professional decision-making [20]. For maker-related courses, this means evaluating one's own design processes from a didactic perspective. The literature and project experiences provide a well-founded training perspective for this. The extent to which one's own maker experience improves future lesson planning cannot be determined from this article.

A manageable design task can serve as a starting point. Students design and test an artifact and document where they needed support. In the subsequent analysis, they distinguish between subject-matter decisions and technical execution: Was the intended form suitable for the investigation? Could it be modeled independently? What kind of help enabled them to continue working? Based on this, they plan a learning activity for children. Peer feedback should separately evaluate the technical function and the expected learning activities, so that a functioning product is not prematurely assessed as a didactically compelling task.

For the cube, this planning can be concretized at the transition from modeling to investigation. If the printed object becomes the starting point for questions about its properties and behavior, students must consider which observations support an explanation and which alternatives remain open. Accordingly, the detector requires a subject-matter clarification of what its ultrasonic feedback indicates. In the digital learning environment, it must be determined whether a gamification element supports subject-specific learning or merely generates additional user actions. The didactic analysis focuses in each case on the connection between the task and the potential for learning.

The technical introduction must cover the operations needed for students to make their own decisions. In the case of CAD design, this may include a brief exercise on positioning and grouping. Afterward, there must be time to test and modify their own designs. If production and presentation are already planned as the final steps, the opportunity to develop further questions based on the artifact's behavior is lost. Reflection should therefore also address what became apparent only through testing and what changes can be justified as a result.

Institutional implementation depends on accessible infrastructure and clearly defined responsibilities. Portable material kits or partnerships with workshops may be suitable for this purpose. In the case of digital fabrication, additional preparation, maintenance, and the processing of print jobs must also be organized. Which of these tasks students should undertake themselves is a pedagogical decision: If, for example, they handle the export and production preparation, the task

expands to include additional technical requirements. If these steps are carried out centrally, the evaluation of the learning process must take this support into account.

8. Implications for Research and Assessment

When investigating maker programs, the data collection method must align with the claimed changes. Self-assessments reveal perceived confidence and progress. Product analyses show the characteristics of a solution but leave the extent of support unaccounted for. Observations provide insight into procedures but capture only documented situations and require transparent rules for interpretation. Combining these data sources allows for the examination of different interpretations. It does not replace a baseline measure when making statements about growth, nor does it replace a follow-up task when making statements about transfer.

The "dice study" links artifact characteristics with statements and observations [14]. This association is more suitable for interpreting individual design actions than an isolated evaluation of the product. Here, too, the question remains as to which actions were performed independently and which were made possible by instruction. In university teaching, successive digital drafts and brief process logs could document when a problem was identified and how it was addressed. A justified change could then be traced based on the initial draft, the review, and the subsequent version. The quality of such a procedure depends on transparent criteria.

The question of input devices can be clarified through comparative studies. These should record previous activities with the devices, experience with CAD, and the operations required for the task. During the task, operational errors would need to be distinguished from spatial or technical misunderstandings. Comparable tasks and documented assistance could reveal whether certain prior experiences facilitate the learning process and what kind of support reduces difficulties. Such a design would translate the reports from the plenary discussion into testable questions. The effectiveness of individual input methods cannot be deduced from the reports themselves.

Furthermore, to advance professionalization, it must be examined whether students develop appropriate instructional decisions based on their own design experience. A positive evaluation of the maker program alone is not sufficient for this. For example, it would be possible to observe whether they accurately diagnose an operational problem, offer appropriate assistance, and subsequently enable students to work independently again. Lesson plans and their testing could further demonstrate whether students plan a path of subject-specific learning that extends beyond the act of making. This would allow educational standards to be linked to specific professional practices.

9. Lessons Learned

This overview clarifies a prerequisite for maker-based teaching: Open design requires a planned approach to the tools used in each case. The competency frameworks already take into account pro-productive digital activities; educators must translate these requirements into concrete terms for their tasks. The three approaches illustrate that this requires different types of knowledge and that technical, subject-specific, and pedagogical challenges must be distinguished from one another. The available findings and project experiences justify this planning task. They do not allow for any conclusions regarding

how frequently the difficulties occur or which introduction is best suited for all groups of learners.

For teacher education, the benefit lies in combining independent design with the analysis of support strategies. Students should be able to understand what decision a task requires, what technical prerequisites are necessary for it, and what insights the subsequent assessment provides. An artifact then documents a workable draft against which subject-specific questions can be further explored. Whether this approach expands professional scope for action must be examined through the planning

and support of corresponding learning processes.

10. Conflict of Interest

The author declares that there are no conflicts of interest.

Author's Contribution

A.-K. Krebs: Concept development, literature review, analysis, drafting of the original manuscript, and revision of the manuscript.

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