The development of pedagogical infrastructures in three cycles of maker-centered learning projects

Sini Maarit Riikonen, University of Helsinki, Finland
Kaiju Kangas, University of Helsinki, Finland
Sirpa Kokko, University of Helsinki, Finland
Tiina Korhonen, University of Helsinki, Finland
Kai Hakkarainen, University of Helsinki, Finland
Pirita Seitamaa-Hakkarainen, University of Helsinki, Finland

Abstract
The purpose of the present investigation was to analyze the pedagogical infrastructures in three cycles of seventh graders' co-invention projects that involved using traditional and digital fabrication technologies for inventing and creating complex artefacts. The aim of the projects was to create high-end multi-material makerspaces by expanding Finnish craft classrooms with instruments of digital fabrication, such as micro-processors, wearable computing (e-textiles), and 3D design and making, for enabling creation of student-designed multi-faceted inventions. Through a qualitative meta-analysis of the three successive learning-by-making projects, we explored the kinds of pedagogical infrastructures required for fostering knowledge-creating practices of learning. Pedagogic infrastructures refer to the designed arrangements and underlying conditions of implementing an extensive study project in classroom practices needed for reaching the learning objectives. We analyzed the epistemological, scaffolding, social, and material-technological dimensions of the enacted pedagogic infrastructures. In accordance with design-based educational investigations, we collected a variety of data (classroom video recordings, teacher and tutor interviews, invention challenges, learning assignments, and working schedules) across three year-long developmental cycles. We discuss the limitations and opportunities of maker-centered learning settings as well as considerations for future development of makerspace as pedagogical innovations for integrating socio-digital and material-technical practices and spaces for learning.

Keywords
Design-based research, digital fabrication, knowledge-creating learning, maker-centered learning, pedagogical infrastructures, socio-digital practices, socio-digital technologies

Introduction
Various educational researchers (Clapp, Ross, Ryan & Tishman, 2016; Honey & Kanter, 2013) have emphasized that elements of maker culture should be rooted in schools to make school learning a more inspiring experience for increasingly socio-digitally engaged young people. Maker-centered learning practices provide ample opportunities for bridging digital divides, overcoming creative participation gaps, and reconnecting informal and formal learning activities (Jenkins, Clinton, Purushotma, Robison, Weigel, 2006; Ito, et. al.,2013). Preparing young people for increasingly innovation-driven professional lives and rapidly transforming knowledge societies, laden with global and local risks and challenges, necessitates putting effort into building innovation capabilities from the beginning of education. Learning by making engages teams of students in working with invention challenges by designing and creating

tangible artefacts with digital and traditional technologies. Makerspaces provide multi-faceted technological (tools) and social (community) resources that enable people to participate in creative practices of inventing and making artefacts (Halverson & Sheridan, 2014). Such practices are often strongly inter-connected with science, technology, engineering, arts, and mathematics (STEAM) learning (Blikstein, 2013; Hatch, 2014; Petrich, Wilkinson & Bevan, 2013). Although many researchers are excited about the educational potential of socio-digital technologies and makerspaces, maker-centered learning, however, often takes place only in afterschool programs with museums, libraries, or DIY and other organizations rather than in schools (Gutwill, Hido & Sindoft, 2015; Halverson & Sheridan, 2014; Kafai & Peppler, 2011). Only a few researchers have examined how learning by making can be integrated with school pedagogical practices for systematically educating personal and collaborative creativity in formal education.

Implementing maker-centered education at schools is challenging because it requires both sophisticated socio-digital teacher competence and cultivation of novel pedagogical practices. Pursuit of maker-centered learning appears to call for non-linear pedagogy that involves teams of students creating unforeseen creative solutions for ill-defined, authentic, and complex challenges (Seitamaa-Hakkarainen, Viilo & Hakkarainen, 2010). Learning to productively deal with uncertainty in the creative process is necessary but may also be challenging for teachers, who must be able to fluently adapt to emergent ideas, unfamiliar technologies, unforeseen epistemic needs, and unpredictable events and actions. There are not many studies regarding adequate collaborative roles of teachers and other facilitators when orchestrating longitudinal maker-centered learning projects. Consequently, there is an urgent need for promoting teachers' professional-collaborative development as well as finding new systematic ways for fostering young students' collaborative learning in technology-enhanced makerspaces.

For synthesizing our experiences of struggling with challenges, we conducted a qualitative meta-analysis of the three maker-centered learning projects by relying on the pedagogical infrastructures framework (Lakkala, Muukkonen, Paavola & Hakkarainen, 2008). Pedagogic infrastructures refer to the designed arrangements and underlying conditions of implementing an extensive technology-mediated learning project needed for reaching the learning objectives in classroom practices. Our investigation aims to examine the essential underlying pedagogical conditions that have to be designed, implemented, and addressed in order to foster students' targeted collaborative making practices at school. We conducted a series of three educational design-based research cycles, which engaged Finnish lower secondary (Grade 7th) students, under the guidance of teachers and researchers, in maker-centered learning for creating co-innovations and building knowledge embedded in artefacts. We describe how the learning-by-making projects evolved through the cycles and how these projects were gradually implemented in regular infrastructures of schooling. Below, we first describe the pedagogical underpinnings that have informed our work. We then present the pedagogical infrastructures framework (Lakkala et al., 2008). Subsequently, we utilize this framework in the qualitative meta-analysis of the three projects, focusing on their contexts, the associated learning activities and teacher teamwork, as well as the tools and materials provided to the students. Finally, we discuss the implications of this study for maker education.

Characteristics of Maker-Centered learning and teaching

Learning through collaborative making is based on a theory of constructionism (Papert, 1980) that regards learners as builders of their own knowledge and views learning in terms of creating artefacts and inventions and cultivating associated novel ways of thinking and acting (Kafai, 2006). To that end, makerspaces provide a wide variety of traditional and digital fabrication tools, materials, and resources for supporting knowledge-creating learning (Paavola & Hakkarainen, 2014). Makerspaces can be seen as dynamic, loft-like spaces where children come with their parents or teachers to pursue their interest-driven making projects, share their design challenges, and work individually or collaboratively—often supported by adult facilitators (Gutwill et al., 2015). Rather than merely working with ideas or building knowledge, participants are challenged to apply their knowledge and understanding for inventing, designing, and making materially embodied artefacts. Maker-centered learning involves students in externalizing their ideas through conceptual (spoken or written ideas), visual (drawings, sketches), or material (3D prototypes and models) artefacts, creating an opportunity for themselves and their peers to build on these ideas, discuss and elaborate upon them, and embody ideas in more advanced artefacts.

Such makerspace philosophy underlines democratization of knowledge and power, open-ended knowledge-creating projects, creativity and design thinking, systematic innovation education, and support from peers, communities, and experts (Sheridan et al., 2014). Maker-centered learning aims to develop “a creative maker mindset” (Dougherty, 2013) in which students develop their creative capabilities and form habits of engaging in the possibility thinking involved in pursuing epistemic objects. Makerspaces are also designed to provide support for personal and social identity development (Fasso & Knight, 2019). The educational importance of participating in these kinds of embodied activities and working with concrete artefacts has been emphasized by many researchers (e.g. Blikstein, 2013; Kafai, Fields & Searle, 2014; Kangas, Seitamaa-Hakkarainen & Hakkarainen, 2013). Maker-centered learning resembles closely modern Design & Technology education (D&T); however, the bases of these two are different. In many countries, D&T education has an established role in the formal educational system and the contents and aims are defined in the curriculum. On the contrary, maker-centered learning originates from informal and non-formal learning environments, such as museums and libraries, where peer supported and networked learning are strongly emphasized. Moreover, maker-centered learning, from its very premise, is transdisciplinary in nature, which is not always the case in formal schooling.

Furthermore, makerspace activities resemble design-studio practices. Sawyer (2018) proposed that design-studio pedagogy represents a historically developed cultural model of teaching and learning creative practices in the craft and design disciplines. In maker-centered learning, the organization of pedagogical settings; the nature of tasks, tools, and methods employed; and social organization should enable the development of students’ collaborative invention skills and understanding of design and making processes. In accordance with authentic contexts, students should be introduced to the process of working with open-ended but focused projects, meeting external constraints determined by an invention challenge (Sawyer, 2018). These tasks should prompt students to experience the complexity of the entire design and making process: defining the constraints, exploring and sketching invention ideas, and experimenting with various materials.

Artefact-mediated learning by making is a nonlinear process where neither can the concrete goals, stages of activity, tools and methods, or resulting products be pre-determined nor can the flow of creative activity be scripted (Sawyer, 2018; Scardamalia & Bereiter, 2014). Investigators of technology-mediated learning have widely adopted such approaches on nonlinear pedagogy, such as Learning by Design™ (Kolodner et al., 2003), project-based learning (Greeno, 2006), and knowledge building (Scardamalia & Bereiter, 2006). In our previous research on maker-centered learning, we created the Learning by Collaborative Design (LCD) (Seitamaa-Hakkarainen et al., 2010; Kangas, & Seitamaa-Hakkarainen, 2018) approach. It is a pedagogical framework for modelling nonlinear design and knowledge-creation processes in educational settings. Designing and making are characterized by emergent "epistemic objects" (Knorr Cetina, 2001; Paavola & Hakkarainen, 2014), that are formed and modified by students during the course of pursuing them. The envisioned epistemic objects guide and direct the process, as they are constantly being further defined and instantiated in a series of successively more refined visualizations, prototypes and design artefacts. In maker projects, the students need to handle various epistemic issues, ranging from making a tangible material object to tackling theoretical scientific concepts. Their epistemic agency is materially entangled, as the material objects involved in the process affect the intertwined generation of design ideas and problems (Mehto, Riikonen, Hakkarainen, Kangas, & Seitamaa-Hakkarainen, 2020). The non-linear pedagogical approaches underline iterative, cyclical processes and the importance of engaging students in sustained efforts to solve meaningful design and making challenges.

Pedagogical infrastructures in the context of Maker-Centered learning

Makerspaces are usually seen as distinct from structured, formal learning environments, such as schools (e.g., Hatch, 2014; Halverson & Sheridan, 2014). Makerspaces emphasize personally significant informal learning and encourage purposeful tinkering and peer-supported inquiry, whereas maker-centered learning in schools tends to be more pre-planned, structured, and guided by teachers (Halverson & Sheridan, 2014; Sheridan et al., 2014; Martinez & Stager, 2013. Facilitation is an important component of the makerspace and involves maintaining the balance between offering enough support while keeping a sufficient distance with self-directed and organized activity. Facilitators are needed for proving guidance through asking questions, modelling, and explaining how things work (Gutwill et al., 2015; Petrich et al., 2013). Further, educators furnished with sophisticated pedagogical knowledge and skills are needed for integrating maker activity with formal school settings (Hsu, Baldwin & Ching, 2017). Nevertheless, the level of supporting structures vary from highly specified procedures to emergent practices in many instructional and pedagogical approaches (Sawyer, 2011). Flexible structuring is based on the idea of scaffolding (Wood, Bruner & Ross, 1976); that is, providing students contextual guidelines or supporting structures for carrying out more complex activities that would otherwise be difficult to achieve. The scaffolds vary from technical scaffolds (worksheet, mind map) to social scaffolds (such as prompts, gestures) facilitated by teachers or peers. Instead of pre-established scripts and pre-set procedures, the practical implementation of emergent processes of nonlinear invention process requires teachers to balance the structuring of a project with a flexible response to the ideas and practices that emerge throughout project (Sawyer, 2011).

Ensuring that design and making activities lead to the intended learning outcomes requires pedagogic planning, teacher engagement, and professional-collaborative learning supported by researchers. While non-linear pedagogy calls for proactively organized team learning, iterative exploration, and systematic harnessing of failures as learning opportunities, teachers have a critical role in orchestrating such collaborative efforts. Sawyer (2011) characterizes the adaptive process of the required creative teaching and learning as “collective improvisation,” guided by being embedded in and happening along the teachers’ practice. They have to create adaptive supporting structures and provide flexible, on-demand scaffolding in response to each student team’s unique situational needs. Adaptive structures refer to the scaffolding provided throughout the learning process for facilitating collaboration and creativity. To facilitate creativity, teachers need to have a clear conceptual and practical understanding of non-linear invention processes, how they are likely to unfold in the classroom, and how they can be deliberately fostered. Productive orchestration requires that the teachers have a clear vision of how instructions or given tasks affect and shape longitudinal design and making processes in embedded settings. According to Sawyer (2018), it is critical to foster focused creativity—too-open design tasks may allow students to fall into familiar patterns or frustration instead of creating new ideas and objects. Simultaneously, the emergent aspects of creative inquiry should be supported both by teachers and peers.

It appears crucial to provide sufficient structural support to facilitate students’ designing and making processes in order to unleash their full creative potentials during the complex invention project. In the context of computer-supported collaborative learning (CSCL), Lakkala et al. (2008) distinguished the epistemological (e.g., creative working with knowledge), cognitive (e.g., modelling inquiry), social (e.g., structuring of collaborative activity; Bielaczyc, 2006), and technological (e.g., digital tools available) infrastructures needed for fostering knowledge-creating learning. These dimensions are the building blocks of the pedagogical infrastructure framework, which Lakkala et al. (2008) define as conditions that were designed and implemented in an educational setting to support learning through targeted knowledge-creation practices. In this study, the notion of pedagogical infrastructure is employed as a metaphor for examining how design and implementation of nonlinear maker-centered learning was organized in the present maker educational setting. While Lakkala et al. (2008; see also, Scardamalia & Bereiter, 2006) argued that educators need to encourage learners to treat conceptual ideas as something that can be jointly improved (epistemological infrastructure), maker-centered learning extended this approach by highlighting importance of creating materially embodied artefacts and the socio-material intertwining (Orlikowski & Scott, 2008) of idea-centered and materially embodied activities in makerspaces. The term “co-invention” is used here to characterize artefacts created during students’ knowledge-creation projects, consisting of intertwined collaborative design and making processes. The purpose of the present investigation was to examine pedagogic infrastructures characterizing three cycles of design experiments concerning maker-centered collaborative learning at lower-secondary educational settings. We examined how epistemological, scaffolding, social, and material-technological infrastructures were implemented across the iterative experiments.

Methodology

Three cycles of co-invention projects

In order to implement and develop maker-centered learning in school settings, we organized three co-invention projects in one lower-secondary school in consecutive springs of 2017, 2018, and 2019. These were part of a larger research project, in which similar projects were organized in ten elementary or lower secondary schools around the great Helsinki area, Finland. The school under study emphasized craft and technology education, holding technology-focused classes for which students were selected through an entrance examination. In the first year, three participating classes were standard class and one technology-focused class (N=70). For practical reasons, only students studying at the technology-focused class participated the project at the second and third year (N=18 in both years). The idea was to focus on developing pedagogical design as well as cross-age tutoring practices in one class. All the successive cohorts of participants taking part in the present project studied in Grade 7 (aged 13 to 14).

The three successive projects investigated provide a good example of educational design-based research (DBR) (Collins, Joseph & Bielaczyc, 2004) with evolving cycles of pedagogical arrangements in one school. In the spirit of research-practice partnership (Coburn & Penuell, 2016), the projects were designed in close collaboration with the teachers according to the practical constraints of school activity. The co-invention challenge, co-configured between teachers and researchers, was the same across the three years: "Invent a smart product or a smart garment by relying on traditional and digital fabrication technologies or other programmable devices or 3D CAD." The projects were initiated in February and involved eight to nine weekly co-design sessions (90–135 minutes per session) during March, April, and May. The students worked in co-invention teams throughout the project.

As crafts is a standard school subject in Finland (Porko-Hudd et al., 2018), two weekly craft lessons were used in the projects. In addition, lessons from other school subjects were used and the integration of the subjects varied each year. In order to assist teachers in dealing with emergent challenges of applying unfamiliar technologies and nonlinear pedagogy, we relied on *team teaching* methodology, where two or more teachers work together in planning and orchestrating learning activities as well as assessing and supporting students' teamwork. During the first project year (2017), two craft teachers orchestrated the project in collaboration with two other teachers, a science teacher and an Information Communication Technology (ICT) teacher. Until now, Finnish craft teachers used to specialize in either textile or technical crafts (Porko-Hudd, Pöllänen & Lindfors, 2018); the two participating craft teachers represented both specializations. In the second project year (2018), the visual arts teacher actively worked with craft teachers whereas the science and ICT teachers were involved only when their expertise was needed. In the third year (2019), the ICT teacher and the science teacher had more central roles in teaching microcontroller programming.

The school had already established practices of using older students as tutors for younger peers. By taking part in the present study, the school aimed at creating a more systematic practice for cross-age peer tutoring. In the present study, Grade 8 students from the technology-focused class tutored their younger peers; in the second and third years, they represented students who had already completed the co-invention project themselves in Grade 7. In addition, the Innokas network (innokas.fi/en) offered support with digital instruments, materials, and coding to the tutor students and, when required, to the inventor teams. The teachers were provided systematic, hands-on training on digital instruments and participatory training of nonlinear pedagogies related to invention processes. In 2018 and 2019, three pre-project workshops were organized, where all teachers participating the research project planned their school projects in teams and received feedback from colleagues and researchers.

Data collection and analysis

A multi-method approach was used for analyzing results of the maker-centered learning practices in order to grasp the systemic features of the maker pedagogies. Each year, we collected video data of five student teams' making activities. The student teams' work was also documented in their sketches, digital portfolios (2018 and 2019), and photographs of final products. The digital tutors and the participating teachers were interviewed in 2017 and 2018. In addition, design assignments and other guidelines for supporting the students' ideation and designing were utilized to support the data analyses. We looked at the practical arrangements of the projects, including social settings and technological and material resources provided for the students. Moreover, in our qualitative meta-analysis, results from our previous research on co-invention processes were utilized (Riikonen, Seitamaa-Hakkarainen & Hakkarainen, 2018; Mehto et al., 2020; Tenhovirta, Korhonen, Seitamaa-Hakkarainen & Hakkarainen, in review). Methods of video analysis were applied to trace student teams' co-invention processes (Derry et al., 2010; Riikonen et al., 2018). The teachers' semi-structured interviews were examined using qualitative content analysis (Saldana, 2015) to find factors affecting the outcomes of team teaching in the context of co-innovation projects. The semi-structured interviews of the 15 peer tutors concerned their tutoring experiences and the challenges encountered. The tutors' skills, motivation, and challenges were analyzed through conducting qualitative analysis of the interview data (Saldana, 2015) on Atlas.ti by relying on a theory-informed and data-driven approach. Table 1 presents the dataset that formed the basis for the present qualitative meta-analysis.

Table 1. A summary of data collected

Data collection	2017	2018	2019
Video data	5 teams' entire design and making process	5 teams' entire design and making process	5 teams' entire design and making process
Project outcomes	Sketches, final outcomes	Portfolios, final outcomes	Portfolios, final outcomes
Teacher interviews	5 teachers	3 teachers	
Tutor interviews	Semi-structured interviews (N=15)	Semi-structured interviews of peer tutors and tutoring model	

The qualitative meta-analysis performed resulted in the pedagogic-infrastructure framework presented in Table 2. The framework was inspired by Lakkala et al. (2008); however, the present maker-centered learning context, as separated from more discursive CSCL, required some modifications. Rather than "cognitive" infrastructure, we address "scaffolding" infrastructure, including not only epistemic but also embodied and tangible support. Furthermore, we propose a broader concept, "material-technological infrastructure," for defining both the technological and material conditions of the educational setting—the combined low- and high-tech capacity of maker education that supports designing, prototyping, and evaluating ideas and artefacts.

Table 2. Pedagogical infrastructures: components, definitions, and essential features of the setting

Component	Definition	Essential features of the setting
Epistemological	**Operational practices of knowledge-creating learning** and the **nature of epistemic processes** that the assignments promote	**Iterative design and making of co-inventions:** Making advancement visible through sketches, prototypes, final products
Scaffolding	**Designed tasks and epistemic and embodied scaffolding structures for** promoting students' capabilities of engaging in nonlinear invention process	**Nature of design tasks:** design briefs and design constraints **Scaffolding for designing:** guidelines relevant for design and making **Teachers' and tutors' support**
Social	**Arrangements to organize** students' team collaboration and social interaction **Shared responsibility**: tasks defined in a way that the accomplishment requires shared responsibility	**Physical and social arrangements** of organizing productive teamwork and interaction **Shared process and object:** the focused collaborative activities and outcomes **Team-teaching practices**
Material-Technological	**Providing** technical advice to the participants and organizing the use of technology. **Functionality of** the tools and their appropriateness for the desired activity	**Techno-material tools and their functionality**: various tools for designing and constructing **Appropriateness of the tools and materials** for the desired activity

Results and discussion

Maker-centered co-invention projects may be experienced as challenging, both by students and teachers, since they involve working with unfamiliar digital fabrication technologies, encountering unanticipated construction problems, and carrying out designing and making to unforeseen directions. In the following section, we present the results, starting with the epistemological infrastructure and scaffolding of the projects. We continue with social and material-technological infrastructures and provide some examples of the data to highlight our interpretations.

Epistemological infrastructure: Engaging students in practices of design and making

The epistemological infrastructure involved in engaging students in knowledge-creation of associated iterative designing and making processes. The design task was open-ended and the teams were given complex, ill-defined tasks to solve through practices that were explicitly and purposefully aimed at creating new co-inventions. The video data revealed that students analyzed, ideated, evaluated, and refined design ideas repeatedly during the project (Riikonen et al., 2018; Mehto et al., 2020). The focused pursuit of knowledge-creation required students to actively work toward a joint epistemic object, listen, understand, and help each other during the process as well as to engage in shared efforts of testing and constructing artefacts (e.g. Barron, 2003).

The given task guided students to iteratively assess and refine their initially fuzzy ideas and finally come up with locally valued co-inventions. The process involved iterative refinement of conceptual ideas through embodied activities of making mock-ups, prototypes, and final products with tangible materials and tools. Teams of student needed to explicate, externalize, and share their emerging design ideas. In other words, *advancement* of invention process was made visible to others and required several cycles of revision and reflection, which sustained improvement of shared and *tangible objects*, such as prototypes and final co-inventions (Mehto et al., 2020). Table 3 highlights the variety of co-inventions made by the student teams. Most teams developed well-articulated design ideas, produced visualizations and prototypes, and tested and refined their co-inventions. Nevertheless, not all design ideas proceeded to final products; especially in the first year, some of the co-inventions were developed only to the prototype stage and one team failed almost completely.

Table 3. Examples of student teams and their co-inventions in 2017, 2018, and 2019

	Name	Team	Basic idea
2017	Bike	3 boys	A three-wheel bike containing smart technologies, such as an environment responsive, rechargeable LED lighting system
	MGG	4 boys	MGG (Mobile Gaming Grip), a pair of handles that improves the ergonomics of a mobile phone while playing games
	Moon	6 girls	A smart outfit for sports, including an environment-responsive lighting system to improve safety
	UrPo	6 boys	A smart insole for sport shoes, including an automatic warming system for winter sports
	Plant	7 girls	An automatic plant care system incorporating decorative elements
2018	Banana light	2 boys, 2 girls	A banana-shaped bending light that attaches to the laptop screen and lights the keyboard.
	Flabe beanie	2 boys, 1 girl	A beanie with an automatically controlled warming system
	FoxFriend	1 boy, 2 girls	A 3D-modelled fox that plays music, talks, and conveys emotions with its LED eyes
	NEObag	2 boys, 1 girl	A backpack with several integrated features controlled by Micro:bit, such as compass, temperature, phone charger, and speedometer
	Smart pillow	1 boy, 2 girls	Smart pillow, with LED lights, snoring detector, and ability to play sound and music
2019	Button Presser I	2 boys, 1 girl	A devise that can be used to press buttons automatically, controlled by Adafruit Circuit Playground Express and a servo-motor
	Moisture sensoring flowerpot	3 girls	3D-printed flowerpot that monitors the moisture level of the soil and notifies using light when the plant needs watering

	Adjustable ruler	1 boy, 1 girl	A 3D-printed ruler that has 6 parts that can be attached to each other with magnets to form different shapes
	SleepSound	2 girls, 1 boy	An ergonomic pillow with inbuilt speakers to play music or other sounds
	Sunny	2 girls, 1 boy	A power bank that utilizes a solar panel and has a 3D-printed case

Figure 1 presents team UrPo's iterative process activities during the development of a smart insole (left) and its various external visual or embodied representations (right). The chart on the left was constructed from the video data by classifying all the team's design activities in 3-minute intervals (See Riikonen et al., 2018 for details). It clearly indicates that the nature of the design process was iterative, yet still progressing. The team produced several tangible prototypes and sketches of alternative structures of the insole, especially elaborating on the placement of the microcontroller.

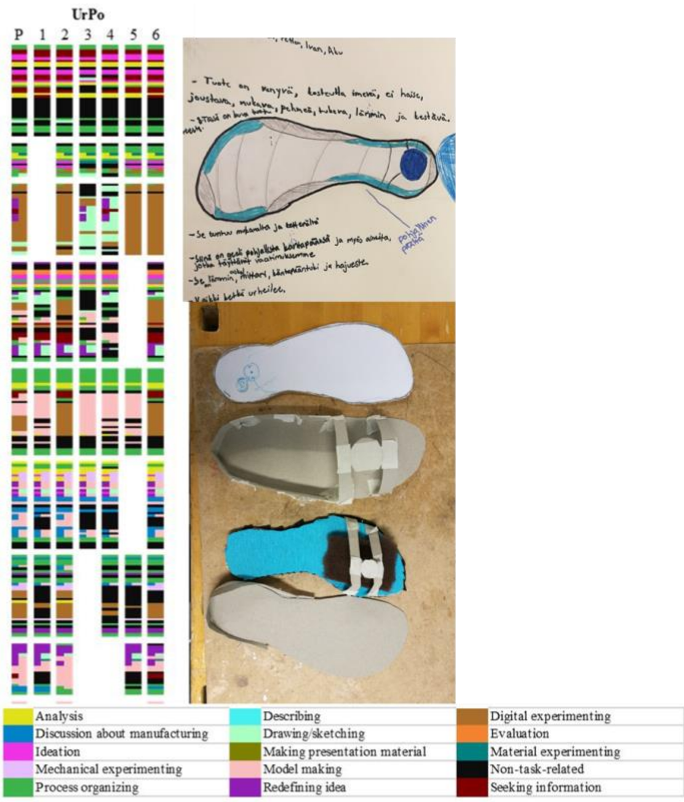

Figure 1. UrPo team's iterative process activities during the co-invention project (left) with some visual and embodied representation produced (right).

In all co-invention projects, the student teams acquired important experience of progressive design and making processes and were able to create unique solutions using both traditional and digital fabrication technologies. Co-inventions can be designed only through repeated iterative efforts, overcoming obstacles, and repeated failures with practical experimenting, obtaining peer and expert feedback, trying again, and ending up with outcomes that may not have been anticipated in the beginning. Further, the students gained confidence in their own ideas and learned to communicate and share them.

Scaffolding: Design tasks, support structures, and nature of knowledge resources

The scaffolding infrastructure was embedded in the design brief and sub-tasks that included the respective support assisting the co-invention process. The maker-centered learning setting provided structures and sequences of continuous working across stages that were self-organized by the teams during the entire design process. The design task itself was a very plain and prototypical example of an open-ended design task in terms of asking one to "invent a smart product or a smart garment by relying on traditional and digital fabrication technologies, other programmable devices or 3D CAD," leaving lot of space for exploring the object of the invention. The task emphasized shared process and team-level objective in terms of indicating that each team should come up with one unique design.

At the beginning of the ideation, various creativity methods were used to stimulate students' ideation and inspire design and making. In the first year, the project was initiated with a two-hour ideation session arranged in collaboration with the Finnish Association of Design Learning. During this session, the students self-organized into teams and constructed the preliminary ideas of their inventions. In the following years, the students visited the Design Museum and in the last year, the visual art teacher gave a presentation of the 5 E's (esthetics, ergonomics, ethics, ecology, and economy) of designing. Table 4 summarizes various methods employed to spark ideation.

Table 4. Various scaffolds provided to students

2017	2018	2019
Workshop by the Finnish Association of Design Learning	Visit to the Design Museum in Helsinki	Visit to the Design Museum in Helsinki The art teacher's presentation of 5 E's (esthetics, ergonomics, ethics, ecology, and economy)
Ideated individually with post-it slips, together on the common big paper	Creation of individual mind map of invention 8x8 method based on each member's own interest and then the whole team common interests	Grouping method in forming teams with name and logo Quick brainstorming method to spark ideas
Digital technology workshop	Digital technology workshop	Two digital technology workshops Electricity workshop (copper tape circuitry) Coding practice with the math teacher
Cross-age tutoring (N=15) from 8th graders	Cross-age tutoring (N=6) from 8th graders	Cross-age tutoring (N=6) from 8th graders
Collection of sketches, prototypes etc.	Group ePortfolio (Sway) with some structure	Group ePortfolio: structured guidelines, facilitation by the Finnish teacher

The actual process began in 2018 and 2019 with ideation sessions led by the visual arts teacher, after which the teams moved to prototyping in their own pace during crafts lessons. The teachers emphasized the iterative nature of designing by encouraging the students to experiment with their ideas. They did not accept the first ideas the students presented but encouraged them to redefine various ideas by testing them. In 2018 and 2019, the students were instructed to record their working on teams' e-portfolios. During the designing and making, both craft teachers provided their expertise and contingent scaffolding (negotiation with materials and representations; technical consultation). The teams mainly organized their processes independently, seeking assistance from the teachers only when needed. Only in instances in which students could not determine how to proceed or became distracted by non-task-related activities did the teachers step in to direct them. During the second and the third year, students' management of the working time was far better than in 2017.

Developing the Peer Tutoring Model for facilitating maker-centered learning

Developing the *Peer Tutoring Model* for supporting maker-centered learning was a fundamental aspect of the school's pedagogical approach (Tenhovirta et al., in review) and provided critical scaffolding structures and practices together with the teachers' support. Each year, before starting the actual project, Grade 8 student tutors arranged digital technology workshops (GoGo Board and Micro:bit microcontrollers) to familiarize each participating 7th Grade class to affordances of digital tools. The workshops fostered ideation on how programmable devices could be utilized in the inventions (Ching & Kafai, 2008). During the project, the peer tutors were present in the classroom, helping the teams with problem solving, troubleshooting, and further developing their ideas.

The original plan for cross-age tutoring was to have an entire grade 8th class as tutors (15 students). The tutors only received a 2-hour training, which made the work very challenging for the less skilled students. Four students voluntarily started, in turn, to spend their free time for improving their skills in programming and became the coordinating "expert" tutors. Although functioning in a role of peer tutor was considered motivating and provided positive prosocial experiences of helping others, the tutors were busy assisting the many tutee teams. In the interviews from 2017, most tutors desired more structured and better supported peer-tutoring processes. The coordinating tutors desired to improve the tutoring system and took an active role in training the next cohort of tutors. To that end, they selected six students from the first tutee group and provided deeper computational training, following which they taught new groups of students together. Slowly, during spring 2018, the coordinator team started to step back, giving the new tutors more space to learn and teach when they entered grade 8. The third cohort of digital tutors took more responsibility for the entire co-innovation process in 2019: they were more involved in the teams' designing, providing their expertise on technology, but also challenging and encouraging the teams to develop their co-inventions further. Their motivation was very high, they received more training and possibilities to teach also teachers and students in other schools or workshops.

The tutors appreciated the independence and responsibility they received:

> *"It became a relationship of mutual respect, because we tutors started to appreciate the job they did after trying it out ourselves, and they respected our commitment. I see this as*

the key. The reason was our commitment and also that of our teachers. They supported us by letting us decide on our own." For some, the tutoring experience had even more far-reaching effects: *It has also had a positive effect on our future plans by, for example, clarifying our study paths. For me, it made really clear that I want to follow technological discoveries in medicine, and it made me choose to go to science and technology class in high school."* The tutors operated like professionals in the field, and through this genuine initiative, advanced a personal identity situated within the domain. As the craft teacher and the principal of the school put it: *"Tutoring model enables students' participation in the school's operation at various levels. It creates a positive, appreciative, heart-to-heart atmosphere in our school."*

Social infrastructure: Arrangements for collaboration and interaction

In this section, we will address social infrastructure enacted in maker-centered learning projects in terms of examining how the teams were formed, the socio-material working space organized, and teamwork processes organized and supported by teachers. When wanting to design successful pedagogical approaches and practices, it is essential to understand how students participate and collaborate in a small group setting with open-ended design and making processes. Small-group collaboration has been investigated rigorously, especially from the perspectives of collaborative talk and actions (Ching & Kafai, 2008; Buchholz, Shively, Pepper & Wohlend, 2014; Kangas et al., 2013). In order to address an invention challenge successfully, a team must simultaneously manage the design task and organize their work processes (Barron, 2003; Kangas et al., 2013); however, they were free to self-organize their working. Although the instruction of co-invention project highlighted collaboration, it was often necessary to divide work because of varying skills and limited number of tools. In such conditions, activity and interaction focused on attaining socially shared objects is likely to facilitate advancement of the co-invention process. Thus, appropriate social and physical settings facilitate participation and sharing of ideas, organize the design process, and support the emerging commitment to a shared object invention.

Students' teamwork

Based on the video data analysis from year 2017, the students focused on collaboration and shared responsibility most of the time. Nevertheless, there were differences in how the teams organized their division of labor during the project. Some teams emphasized the importance of mutual understanding, and, accordingly, encouraged each other so that everyone's voice was heard. On the other hand, there were instances of an individual student taking a leadership role, but that was not the general pattern. While the smaller teams (Bike and MGG) worked throughout the whole process in very intensive and close collaboration, the process was more scattered in the larger teams (Moon, UrPo, and Plant) (Riikonen et al., 2018). The collaboration was more democratic and balanced in the smaller than in the larger teams, and there occurred a considerable amount of off-topic talk indicating that not all members were occupied enough. Especially during the first project year, some teams were quite big and had challenges related to project and time management. The following teamwork situation of the UrPo team, illustrated in Figure 2, is a good example of the difficulties that the bigger teams faced with process organizing and focusing on the task. One of the group members, Craig, has already left the table to talk with a friend from another team. Another team member, Robin, is sitting away from the rest of the group and not engaging in the teamwork. The remaining four team members are socially engaged but simultaneously carry on two different conversations across the table. Bob tries to engage Ray in the design task, while Kevin and Jared are having non-task-related conversation. With everyone talking over to each other, the conversation is very scattered. Bob tries for a while to get Ray working with him on the design task but gives up and all four carry on non-task-related discussion:

Bob: Ray, what kind of an insole would you like to design?
Ray: I don't even have paper!
Kevin: Jared, I'm mimicking Elixir Pump!
Bob: Take some paper from Craig, he doesn't need two.
Jared: I never use Elixir Pump!
Ray: See, I actually have some [paper].
Bob: But take the shoe also from Craig!
Ray: I don't have a pen.
Jared: How on earth did you do that [a mimicking sound that Kevin made]?

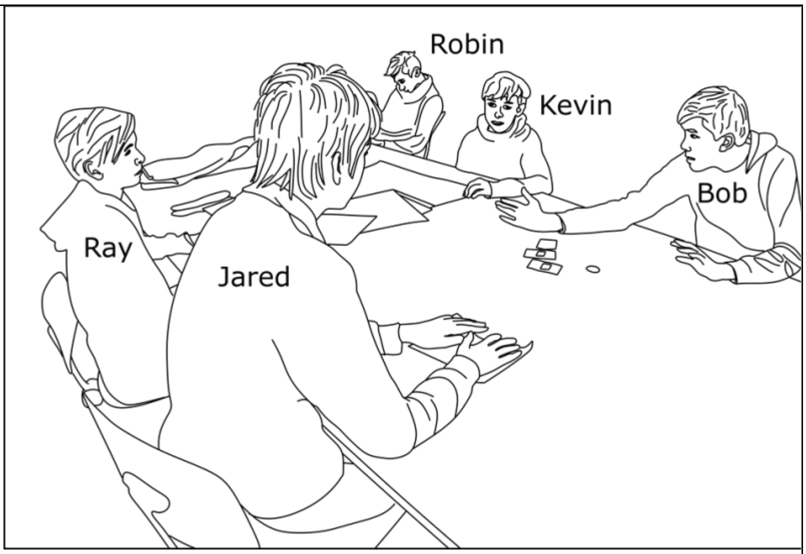

Figure 2. Example of difficult teamwork situation of the UrPo team.

Findings indicating that team size had a significant effect on the nature of peer collaboration led to the reduced team size during the second and third years and, consequently, the teamwork became smoother and more focused. In the first year, the visiting designer let the students to form teams by themselves. Consequently, uneven and big teams, up to 6–7 members in each, were formed, consisting of girls- or boys-only teams with best buddies together. Later, the teachers were encouraged to allow only 3–4 member teams. In year 2018, the teachers organized a lottery in order to form reasonable sized groups consisting of both genders. Not all pupils were, however, willing to work in such random teams, leading to some conflicts. Hence, some teams were rebuilt to provide a good start for the project. There were two students who wanted to work on their own idea, which they had invented before the project had started, and they were allowed to do so. In the third year, the teachers carefully planned and formed the teams before the project started. Teaming up was also supported with the grouping method, during which the students created a team name and a logo.

Team teaching

The collaboration between the teachers played an important part in negotiating scaffolding and orchestration challenges of the projects. During the first year, the initial plan was to engage all five subject teachers in the process, but this both turned out to be hard to arrange in practice and all the teachers were not needed in all stages of the process. Therefore, the teachers' teamwork structure was developed further. In the last year, the structure included "three layers," where the craft teacher led the team by organizing schedules and informing others in the first layer. In the second layer, both craft teachers and the art teacher orchestrated the process and were responsible for planning and implementing the project. Finally, in the third layer, the ICT, math, physics, and Finnish teachers provided their expertise to the student teams when needed.

Based on the teachers' interviews, co-planning was practiced through ideation, organization, and evaluation of the project. The teachers experienced joint ideation as an empowering method for planning both learning contents and methods. They also seized co-planning as an opportunity for project organizing, scheduling the project, and dividing responsibilities among the teachers. In addition, the teachers felt that collaborative evaluation of student work increased objectivity. They felt especially challenged, however, by the limited time allocated for co-planning sessions:

> *"-- we meet in the passage or visit each other's classrooms in the middle of a lesson, so that we don't have time, like, for breaks or anything. If we want to develop this further, it is important have co-operation time, or what it is, then it would be possible to really share experiences with a colleague undisturbed*." (Teacher 3)

> *"And then [we need to design] the contents of this project and how we are going to proceed. But now it kind of develops on the way. It develops according to how we make progress. Yes, during many breaks and many days when we work close to each other, I run there or she (another teacher) comes here, she comes here to ask, we take the time [to co-operate]whenever possible."* (Teacher 1)

Nevertheless, the teachers ensured that the established school practices and engaging team-teaching culture supported the planning of co-invention projects. Teachers reported having very fluid practices of team collaboration in terms of assuming various roles—for example, that of leader or organizer of practicalities—based on contextual needs. The key was to end up with roles that divide responsibility to each member of the team in a way that allows the students to benefit together from team teaching. Further, the teachers emphasized the key importance of sharing expertise between team members and expanding the expertise available for fostering integrative co-invention projects. The teachers felt that without cross-subject support, the implementation of co-invention projects would become much more challenging.

Material–Technological infrastructure: Availability and functionality of materials and technologies

In our project settings, the concrete tools and materials for defining, refining, and further developing invention ideas characterized the Material-Technological infrastructure. Sufficiently rich material resources and design and making tools are crucial for sparking creativity and object-driven pursuit in co-invention teams. Visual and tangible external representations in various phases of the invention process provided multi-faceted prompts for testing and refining ideas and objects generated. Hence, it is crucial to analyze how the provided tools and materials supported or hindered the production of representations.

During the co-invention project, the students worked in teams in three different studio-type classrooms: starting from the visual arts room and then moving between textile craft and technical craft classrooms, depending on what was needed for the invention process. All the spaces were well-organized, offering various resources, tools and machines, and enough collaborative working space. Together, the three classrooms provided the socio-material makerspace with diverse materials and tools needed for diverse co-inventions. In various phases of the co-invention project, such as visualizing, building mock-ups or prototypes, the teams worked with different tools and materials, using both traditional and digital technologies. All the tools and materials served certain functionality and relevance for the focused creative activity. Most of the sketches were rough, outline drawings including some written notes. The drawings were, however, understandable within the team, and they were annotated with crucial information. Interaction with materials is not only physical but spurs thinking as well. The digital tools utilized varied from one year to another. While GoGo Board and Adafruit Flora and Gemma microcontrollers were used in the first year, Micro:bit and Adafruit Circuit Playground took over during the following ones. Further, modeling with cardboard, clay, wire and other simple materials was used along with 3D CAD modeling and 3D printing. Using various materials for making the initial prototypes assisted the students in constructing 3D forms, experimenting with preliminary solutions, and examining some details on the surface (see Figure 3).

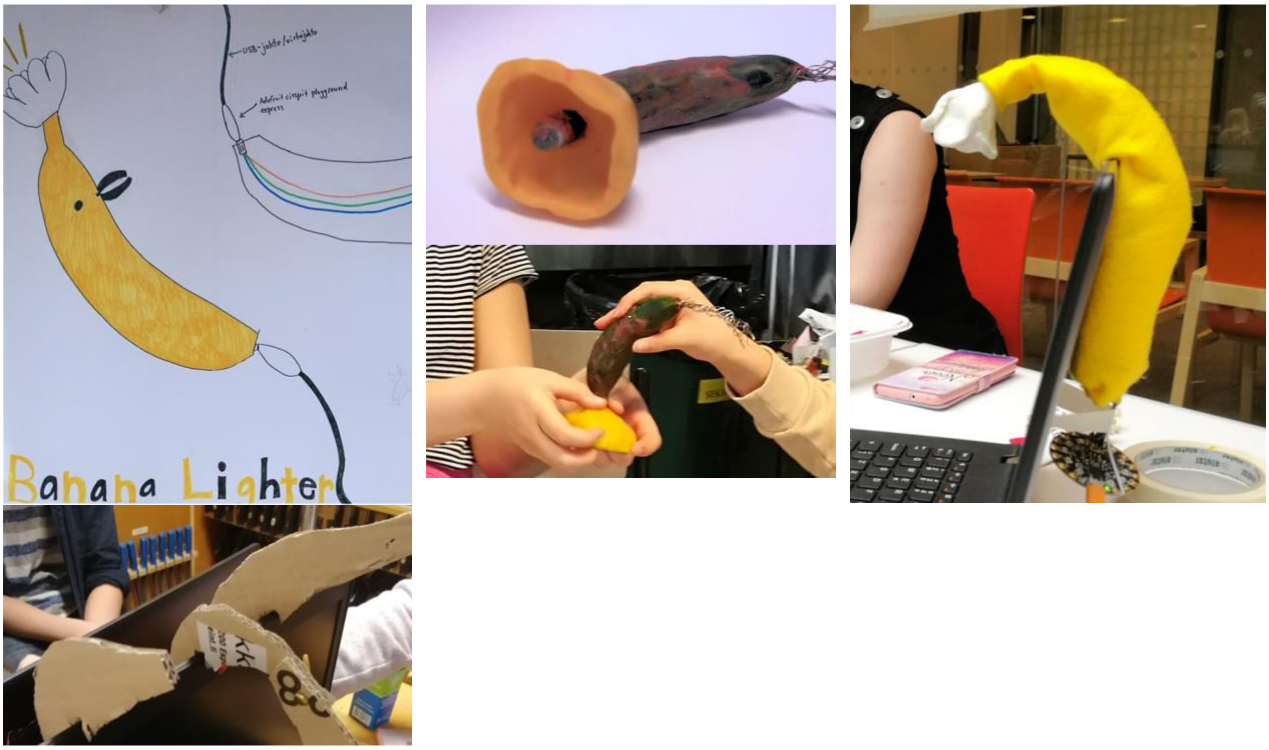

Figure 3. Various materials and tools used in different phases of designing the Banana Lighter.

However, the materials and tools used with the unscripted sessions can both constrain and enable division of labor. For example, coding with a singular laptop constrains the possibility for simultaneous participation by multiple students. This indicates that it is not only social interaction that affects the nature of collaboration but also available tools, spaces and materials play an important role during design and making.

Conclusion

The aim of the study was to synthesize findings across three successive co-invention projects. To that end, we examined the enacted pedagogical infrastructures of maker-centered learning in basic education across epistemological, scaffolding, social, and material-technical infrastructures. Overall, the present investigation addressed various critical aspects of supporting teaching and learning in makerspace settings. The design studios approach is the traditional and widely used educational model and makerspaces strongly rely on it. The central aim of studio-based working is to create a socio-material space for fostering focused designing, invention, and making of materially embodied artefacts. In the first instance, the studio method was used to provide students with socio-collaborative experience of creating inventions. Our investigation reveals that educational maker learning could be a socio-collaboratively emergent process. In accordance with knowledge-creating epistemology, the student teams transformed their ideas into various material forms and created iteratively refined artefacts according to the specific requirements of their co-invention. Further, the participants were guided to use professional creativity methods, such as brainstorming, visualizing, and materializing design ideas, at different phases of their process to assist their knowledge-creating pursuits. To make students more aware of the iterative and nonlinear nature of making, we could have more explicitly introduced some pedagogical frameworks, such as the LCD model, for helping conceptualize the iterative process of creating innovation.

Many educators (Binkley et al., 2012) have emphasized the twenty-first century skills and socio-digital competences that students cultivate in makerspaces. Fasso and Knight (2019) noted, however, that there are still no clear links between design and making practices and typical curriculum of school. In many countries, educational makerspaces have not been considered in the curricular planning. An additional problem appears to be that materials and activities included in the STEAM curriculum tend to lose the richness of socially-embedded authentic and contextual activities involved in regular makerspaces as well as focus on pursuing genuine design, invention, and making objects with emergent technologies (Fasso & Knight, 2019). Nevertheless, the current Finnish National Core Curriculum (FNBE, 2014) highlights creativity, innovation, and socio-digital skills as crucial transversal competences. Moreover, the curriculum encourages and even requires the integration of various subjects in terms of integrative or thematic study projects providing opportunities for sustaining maker culture in collaboration between the craft and other school subjects. The kinds of co-invention projects described in this study provide many opportunities for integrating various subjects and implementing transversal competences. Naturally, these requirements also create pressure for schools and teachers, as new kind of technological and pedagogical expertise and resources are needed.

Implementing makerspaces in educational settings requires fostering teachers' professional expertise, cultivating practices and methods of nonlinear pedagogy, focusing heavily packed curriculums on essentials, developing formative approaches on student assessment, and learning to use student-diversity as an asset rather than a problem (Hira, Joslyn & Hynes, 2014). However, in many cases, it is hard to find appropriate technological resources and manage rapidly changing technologies at studio-based classrooms. Designing the functioning of the makerspace requires combined expertise in pedagogy and STEAM subjects (Fasso & Knight, 2019). In our co-invention projects, there was a multi-disciplinary teacher team (including a subject teacher specialized in crafts, several other class and subject teachers) and participating teachers were provided extra support by peer tutors, researchers, visiting experts, and museum visits. Teacher collaboration interconnected various subject domains and associated expertise in nonlinear pedagogy. The analysis revealed, however, that we need to develop project documentation by providing new tools (e.g. ePortfolio) and more structural guidelines that support students or teams' reflections in and on action as well as assist in providing formative feedback.

It should be noted that the school participating in our study was an ordinary school in a middle-class suburban area, however, the school community has for years been devoted to developing practices that support transdisciplinary co-teaching and distribution of teachers' and students' technological expertise. Furthermore, in the larger research project that this study is part of, we have altogether 10 participating schools, which all are ordinary public schools with typical teachers and students. According to our experiences, developing maker-centered learning is not dependent on teachers' sophisticated socio-digital competencies, but relies more on the opportunities provided by the curriculum and the schools' structural practices.

Knowledge creation is an improvisational activity, where the best teaching is characterized as *disciplined improvisation* (Sawyer, 2018) in terms of providing a flexible space for maker-centered learning mediated by scaffolding structures and practices, such as design briefs, ideation exercises, sketching, rapid prototyping, and team presentations; it is similar to professionally performed improvisations in many areas. Further, maker-centered learning settings should provide a variety of open-ended design tasks that, among other things, provide guidance on considering and exploring user needs. Along with emphasizing the open-ended and emergent aspects of design and making, it is critical also to be focused: Too open design tasks can lead to returning to familiar patterns or frustration in searching for conventional adequacy instead of creating novel ideas (Sawyer, 2018). To conclude, the lessons learned while developing maker-centered learning practices can be crystallized as follows: 1) Emphasis must be placed on longstanding knowledge-creating projects that provide ample opportunities for sustained iterative working and learning from failures for improving objects of design and making; 2) real-time teacher and peer tutor guidance and embedded scaffolds must be used for inspiring the ideation and digital experimentation, making successively more refined artefacts; and 3) guidelines and tools (e.g. ePortfolio) must be provided for documenting and reflecting on the advancement of invention process and develop of associated capabilities, maker mindset, and creative identities.

Acknowledgements

This research was supported by the Academy of Finland (Grant 286837, Co4Lab) and Strategic Research Grant 312527 of the Academy of Finland (Growing Mind, see https://growingmind.fi/).

References

Barron, B. (2003). When smart groups fail. *The Journal of the Learning Sciences*, *12*(3), 307–359.

Bielaczyc, K. (2006). Designing social infrastructure. *Journal of the Learning Sciences*, *15*(3), 301–329.

Binkley, M., Erstad, O., Herman, J., Ripley, M., Miller-Ricci, M., & Rumble, M. (2012). Defining twenty-first century skills. In E. Care, P. Griffin, & B. McGaw (Eds.), *Assessment and teaching of 21st Century Skills* (pp. 17–66). Springer.

Blikstein, P. (2013). Digital fabrication and “making” in education: The democratization of invention. In C. Büching, & J. Walter-Herrmann (Eds.), *FabLab : Of machines, makers and inventors* (pp. 203–222). Transcript.

Buchholz, B., Shively, K., Pepper, K., & Wohlend, K. (2014). Hands on, hands off: Gendered access in crafting and electronics practices. *Mind, Culture and Activity*, *21*(4), 278–297.

Ching, C. C., & Kafai, Y. (2008). Peer pedagogy: Student collaboration and reflection in a learning-through-design project. *The Teachers College Record*, *110*(12), 2601–2632.

Clapp, E. P., Ross, J., Ryan, J. O., & Tishman, S. (2016). *Maker-centered learning: Empowering young people to shape their worlds.* Jossey-Bass.

Coburn, C. E., & Penuel, W. R. (2016). Research-practice partnership in education. *Educational Researcher*, *45*, 48–54.

Collins, A., Joseph, D., & Bielaczyc, K. (2004). Design research: Theoretical and methodological issues. *The Journal of the Learning Sciences*, *13*, 15–42.

Dougherty, D. (2013). The maker mindset. In M. Honey, & D. E. Kanter (Eds.), *Design, make, play: Growing the next generation of STEM innovators* (pp. 7–11). Routledge.

Derry, S. J., Pea, R. D., Barron, B., Engle, R. A., Erickson, F., Goldman, R., Engle, R., Erickson, F., Goldman, R., Hall, R., Koschmann, T., Lemke, J., Sherin, M. & Sherin, B. (2010). Conducting video research in the learning sciences: Guidance on selection, analysis, technology, and ethics. *Journal of the Learning Sciences*, *19*(1), 3–53.

Fasso, W., & Knight, B. (2019, online first). Identity development in school makerspaces: Intentional design. *International Journal of Technology and Design Education*. https://doi.org/10.1007/s10798-019-09501-z

Finnish National Board of Education FNBE (2014). *The National core curriculum for basic education.* Retrieved from http://www.oph.fi/download/163777_perusopetuksen_opetussuunnitelman_perusteet_2014.pdf

Gutwill, J., Hido, N., & Sindoft, L. (2015). Research to practice: Observing learning in tinkering activities. *Curator*, *58*(2), 151–168. https://doi.org/10.1111/cura.12105

Greeno, J. G. (2006). Learning in activity. In R. K. Sawyer (Ed.), *The Cambridge handbook of the learning sciences* (pp. 79–96). Cambridge University Press.

Halverson, E., & Sheridan, K. (2014). The maker movement in education. *Harvard Educational Review*, *84*(4), 495–504. https://doi.org/10.17763/haer.84.4.34j1g68140382063

Hatch, M. (2014). *The maker movement manifesto*. McGraw-Hill.

Hira, A., Joslyn, C. H., & Hynes, M. M. (2014, October). Classroom makerspaces: Identifying the opportunities and challenges. In *IEEE Frontiers in Education Conference* (FIE) (pp. 1–5). IEEE.

Honey, M., & Kanter, D. (2013). Introduction. In M. Honey, & D. Kanter (Eds.), *Design, make, play: Growing the next generation of science innovators* (pp. 1–6). Routledge.

Hsu, Y. C., Baldwin, S., & Ching, Y. H. (2017). Learning through making and maker education. *Tech-Trends*, *61*(6), 589–594. https://doi.org/10.1007/s11528-017-0172-6

Ito, M., Gutiérrez, K., Livingstone, S., Penuel, B., Rhodes, J., Salen, K., Schor, J., Sefton-Green & Watkins, S. (2013). *Connected learning: An agenda for research and design*. Digital Media and Learning Research Hub. http://eprints.lse.ac.uk/48114/

Jenkins, H., Clinton, K., Purushotma, R., Robison, A. J., & Weigel, M. (2006). *Confronting the challenges of participatory culture: Media education for the 21st century.* The MIT Press.

Kafai, Y. (2006). Playing and Making Games for Learning: Instructionist and Constructionist Perspectives for Game Studies. *Games and Culture*, 1(1), 36–40.

Kafai, Y., Fields, D., & Searle, K. (2014). Electronic textiles as disruptive designs: Supporting and challenging maker activities in schools. *Harvard Educational Review*, *84*(4), 532–556.

Kafai, Y. Peppler, K., (2011) Youth, technology, and DIY: Developing participatory competencies in creative media production. *Review of research in education* 35 (1), 89–119.

Kangas, K., Seitamaa-Hakkarainen, P., & Hakkarainen K. (2013). Design Thinking in Elementary Students' Collaborative Lamp Designing Process. *Design and Technology: an International Journal 18(1)*, 30–43.

Kangas, K & Seitamaa-Hakkarainen, P (2018). Technology Education: Collaborative Design Work in Technology Education. In de Vries, M. (ed.), *International Handbook of Technology Education* (pp. 597–609). Springer.

Knorr-Cetina, K. (2001). Objectual practice. In K. K. Cetina, T. R. Schatzki, & E. Von Savigny (Eds.), *The practice turn in contemporary theory* (pp. 175–188). Routledge.

Kolodner, J. L., Camp, P. J., Crismond, D., Fasse, B., Gray, J., Holbrook, J., & Ryan, M. (2003). Problem-based learning meets case-based reasoning in the middle school science classroom: Putting Learning by Design™ into practice. *Journal of the Learning Sciences*, *12*(4), 495–547.

Lakkala, M., Muukkonen, H., Paavola, S., & Hakkarainen, K. (2008). Designing pedagogical infrastructures in university courses for technology-enhanced collaborative inquiry. *Research and Practice in Technology Enhanced Learning*, *3*(1), 33–64.

Martinez, S. L., & Stager, G. (2013). *Invent to learn: Making, tinkering, and engineering in the classroom*. Constructing Modern Knowledge Press.

Mehto, V., Riikonen, S., Hakkarainen, K; Kangas, K, & Seitamaa-Hakkarainen, P. (2020, online.) Epistemic roles of materiality within a collaborative invention project at a secondary school. *The British Journal of Educational Technology*,

Orlikowski, W., & Scott, S. (2008). Sociomateriality. *The Academy of Management Annals*, *2*(1), 433–474.

Paavola, S., & Hakkarainen, K. (2014). Trialogical approach for knowledge creation. In S. C. Tan, H. J. So, & J. Yeo (Eds.), *Knowledge creation in education. Education innovation series* (pp. 53–73). Springer.

Papert, S. (1980). *Mindstorms: Children, computers, and powerful ideas*. Basic Books.

Peppler, K. (2013). STEAM-powered computing education: Using e-textiles to integrate the arts and STEM. *Computer*, *46*, 38–43.

Peppler, K., & Glosson, D. (2013). Stitching circuits: Learning about circuitry through e-textile materials*. Journal of Science Education and Technology*, *22*, 751–763.

Petrich, M., Wilkinson, K., & Bevan, B. (2013). It looks like fun, but are they learning? In M. Honey, & D. Kanter (Eds.), *Design, make, play: Growing the next generation of STEM innovators* (pp. 50–70). Routledge.

Porko-Hudd, M., Pöllänen, S., & Lindfors, E. (2018). Common and holistic crafts education in Finland. *Techne Serien A*, *25*(3), 26–38.

Riikonen, S. M., Seitamaa-Hakkarainen, S. P. & Hakkarainen, K. P. J. (2018). Bringing Practices of Co-Design and Making to Basic Education. In Kay, J. & Luckin, R. (Eds.), *Rethinking Learning in the Digital Age: Making the Learning Sciences Count, 13th International*

Conference of the Learning Sciences (ICLS) 2018, 2018 (2), 248–255. London: International Society of the Learning Sciences,

Saldaña, J. (2015). *The coding manual for qualitative researchers.* Sage.

Sawyer, R. K. (2011). What makes good teachers great? The artful balance of structure and improvisation. In R. K. Sawyer (Ed.), *Structure and improvisation in creative teaching* (pp. 1–24). Cambridge University Press.

Sawyer, R. K. (2018). Teaching and learning how to create in schools of art and design. *Journal of the Learning Sciences*, *27*(1), 137–181.

Scardamalia, M., & Bereiter, C. (2006). Knowledge building. In R. K. Sawyer (Ed.), *The Cambridge handbook of the learning sciences* (pp. 97–115). Cambridge University Press.

Scardamalia, M., & Bereiter, C. (2014). Smart technology for self-organizing processes. *Smart Learning Environments*, 1(1), 1–13.

Sheridan, K., Halverson, E. R., Litts, B., Brahms, L., Jacobs-Priebe, L., & Owens, T. (2014). Learning in the making: A comparative case study of three makerspaces. *Harvard Educational Review*, *84(*4), 505–531.

Seitamaa-Hakkarainen, P., Viilo M. & Hakkarainen K. (2010). Learning by Collaborative Designing: Technology-enhanced Knowledge Practices*. International Journal of Technology and Design Education. Vol. 2*(2), 109-136.

Tenhovirta, S., Korhonen, T., Seitamaa-Hakkarainen, P & Hakkarainen, K. (in review) Cross-age Peer Tutoring in a Technology-enhanced STEAM Project at a Lower Secondary School. *International Journal of Technology and Design Education*.

Wood, D., Bruner, J., & Ross, G. (1976). The role of tutoring in problem solving. *Journal of Child Psychology and Psychiatry and Allied Disciplines*, *17*, 89–100.