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The roles of material prototyping in collaborative design process at an elementary school

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Abstract

Co-invention projects in elementary school engage pupils in complex, open-ended design tasks in a practical, hands-on way. Physical materials are an intrinsic part of design, involving trasformation of conceptual ideas into material forms, such as prototypes. These tangible objects mediate embodied thinking and act as material-social mediators of knowledge creation processes. However, the material properties of the designed artifact and pupils' varying skills and levels of material knowledge constrain the design process.

While previous studies of materiality in design have mainly focused on adults, this study aims to analyze and describe the different roles of material prototyping in an elementary school collaborative design process. A co-invention process was conducted in a Finnish elementary school during spring 2017, with the task of designing solutions for everyday problems. The data consisted of six video recorded design sessions, where small teams of 5th graders prototyped their inventions. We analyzed the video data across macro-, intermediate-, and micro-levels.

The results revealed that pupils used prototypes as mediators for ideation and collaboration. They tested their ideas with prototyping, and material manipulation occurred during collaborative ideation. Material representations supported the verbalization and demonstration of ideas. Some challenges also emerged; prototype construction was a slow and laborious process, the division of labor tended to be unevenly distributed, and the model took a dominant role over the designed artifact. We conclude that support from the teacher and the learning environment is critical for utilizing the full potential of material manipulation in an elementary school setting.

Keywords

prototyping, collaborative designing, elementary school, maker-centered learning, materiality, video analysis

Introduction

Maker-centered learning offers pupils the opportunity to engage with the world by designing, making, and knowledge creating (Clapp, Ross, Ryan & Tishman, 2016; Peppler, Halverson & Kafai, 2016; Seitamaa-Hakkarainen & Hakkarainen, 2014). In recent years, much research has been conducted to investigate pedagogies and practices of maker-centered learning, where making broadly refers to various activities of creating, designing, building, and tinkering (Ryan, Clapp, Ross & Tishman, 2016). Currently, many educators have been interested in the global maker movement as it has provided various informal and out-of-school hands-on learning opportunities for pupils to enhance and cultivate skills in the fields of science, technology, engineering, arts and mathematics (STEAM) through creative use of digital fabrication technologies (Honey & Kanter, 2013; Blikstein, 2013). While maker-centered learning emphasizes self-directed learning, engagement, risk taking and using failures as creative learning opportunities, it also highlights the importance of iterative processes of designing and making in collaborative settings (Ryan et al., 2016). Although in the out-of-school programs, students usually work on individual projects, solidarity with others and the opportunity to contribute to their work are highlighted (Petrich, Wilkinson & Bevan, 2013, 157). In a school context, collaborative work is more common: the design project emphasizes sharing and pursuing a shared purpose with other team members, and the team builds on and adapts to ideas, while helping each other to achieve goals (Kangas, Seitamaa-Hakkarainen & Hakkarainen, 2013a). Learning to use various traditional and digital tools for creative purposes and understanding the potentiality of materials are all important components of maker-centered learning pedagogies (Ryan et al., 2016; Seitamaa-Hakkarainen & Hakkarainen, 2017).

Challenging and authentic design tasks provide meaningful contexts for young pupils to participate in practices of knowledge-creating learning in an experimental, hands-on, and collaborative way. "Designerly" ways of thinking and augmentation of reasoning process by the manipulation of materials are the most important qualities of design learning and making; these require creative generation of ideas, as well as critical thinking, particularly when conceptual ideas and material aspects of the process reciprocally support one another (Kangas, Seitamaa-Hakkarainen & Hakkarainen, 2013a). The emerging design artifacts and prototypes provide implicit hints and guidelines regarding how to further elaborate ideas (Knorr-Cetina, 2001); hence, the creative process has a material basis. According to Deininger, Daly, Sienko, and Lee (2017), prototyping and material model making can be seen as a combination of different techniques that allows physical or visual form to be given to a design idea (Alesina & Lupton, 2010; Kelley & Littman, 2006), which can be evaluated from various perspectives. The invention process is inherently object-driven in nature, involving a nonlinear creative pursuit of envisioned "epistemic objects", instantiated in a series of successively more refined artifacts and productions (Knorr-Cetina, 1999, 2001; Rheinberger, 1997; Paavola & Hakkarainen, 2014; see also Wagner, 2012). Such epistemic objects are defined by their openness, their "lack of completeness of being" and "capacity to unfold indefinitely" through successive imperfect but affect-laden instantiations (Knorr-Cetina, 2001). Thus, the iterative interaction between thinking and making is pivotal (Kimbell & Stables, 2007) and physical materials are an intrinsic part of the process: conceptual design ideas are transformed into various material forms, such as sketches, mock-ups, prototypes and final artifacts.

Material embodiment appears to be a constitutive characteristic of maker-centered learning that provides ample opportunities to observe, imitate, and appropriate instrument- and materially mediated creative activities. Learning by making is entangled not only with human but also non-human agents, such as the material tools, resources, and spaces. Presumably, the making process relies on an "embodied mind" where mental imagery together with material exploration support the dynamic generation of successively more refined artifacts embodying progressing design ideas. In design and maker-centered learning children learn technological skills by engaging with materials and building structures or devices (Rowell, 2004). Prototyping with materials includes analyzing design constraints and seeking feedback through experimentation with materials and structures. Materiality concretizes the iteration in the design process: materialization of design ideas makes them visible for joint evaluation and development (Binder, Michelis, Ehn, Jacucci, Linde & Wagner, 2011), and material representations can be tested and further refined (e.g. Welch, 1998). Designing and making have enormous potential to provide direct experience of new materials, tools and technologies. Moreover, design and making activities should develop young pupils' personal and social abilities to enhance and transform ideas, provide opportunities for inventive solutions, and confidently express ideas about sketching and model making (Welch 1998; Welch, Barlex & Lim, 2000). Several researchers have noted that small children are not motivated to use drawings (Fleer, 2000; Welch, Barlex & Lim, 2000), but instead prefer first to explore with materials and then to construct an artifact. In maker-centered settings, pupils should be encouraged to use different kinds of visualization methods (including 3D CAD visualizations) to externalize their design ideas, build various mock up models, or construct 3D prototypes.

Although the importance of materiality and ability to materialize design ideas has been highlighted, most of the previous research on materiality in design has focused on professional designers or university-level design students (e.g. Gore, 2004; Poulsen & Thøgersen, 2011; Vrencoska, 2013; Lahti, Kangas, Koponen & Seitamaa-Hakkarainen, 2016). Materiality and materialization have rarely been the main focus of studies on young pupils' design and making processes, although a few studies emphasize the importance of materiality (e.g. Kangas et al., 2013a; 2013b; Rowell, 2002; Welch, 1998; Welch, Barlex & Lim, 2000). Therefore, the particular objective of the present study was to analyze the role of prototyping (i.e., mock up models) and material model making in elementary school pupils' collaborative design process. Accordingly, we address the following three research questions:

- How are prototypes used for refining design ideas or the prototype itself?
- How are prototypes used as social mediators of a collaborative design process?
- How do the material properties of prototypes become visible in collaborative design processes?

In the following, we will take three perspectives on material prototyping: (1) prototypes as aids for thinking, (2) prototypes as social mediators, and (3) prototypes as material constraints to the process. In the present study, we use prototyping and prototype to cover different material representations produced during the co-invention process such as mock up-models and various material models.

Three perspectives on material prototyping

Kangas and Seitamaa-Hakkarainen (2018) describe collaborative designing as an iterative and cyclical process in which the participants share their expertise in creating a meaningful and authentic design context for analyzing design constraints and proposing ideas as well as for providing feedback in order to develop a shared design object. According to Abrahamson and Lindgren (2014), material objects mediate embodied learning. Building shared prototypes and artifacts makes learning and collaboration tangible. Additionally, Rowell (2002) emphasizes that physical materials stimulate collaboration. These interpretations support the fact that prototypes aid ideation and thinking in collaborative settings.

(1) Prototypes as aids for thinking

Manipulation of materials is a means of embodied thinking, and prototyping can be a way to externalize ideas that might otherwise be difficult to imagine, explicate and verbalize. A prototype could be utilized for testing functional and structural aspects of design (Binder et al., 2011), or visualizing the design ideas being developed (Ramduny-Ellis, Dix, Evans, Hare & Gill, 2010). Illum and Johansson (2012) have pointed out that material representation supports the verbalization of abstract ideas (see also Kangas et al., 2013a; 2013b; Welch, 1998). According to Poulsen and Thørgesen (2011), embodied thinking, i.e., thinking enhanced by working with material artifacts, is an intrinsic part of designing. Kimbell and Stables (2007) emphasize, that complementing cognitive process of imagining by concrete modelling is essential for design capability. In addition, materials offer valuable feedback through iterative model making (e.g. Gore, 2004; Jacucci & Wagner, 2007). Kangas et al. (2013a; 2013b) have studied artifact design in elementary-level education and discovered that embodied activities could help young pupils move into knowledge-creation processes otherwise beyond their capabilities. In professional designing, the various visual representations, mock up models and more detailed prototypes are created frequently and inexpensively at various phases of the process so as to assist designers in identifying design issues, discovering opportunities, and quickly eliminating less promising solutions (Alesina & Lupton, 2010; Deininger et al., 2017). Choosing a specific goal for prototyping is crucial also in the elementary school context (Klapwijk & Rodewijk, 2018). Usually, novice designers consider prototypes as models created towards the end of a process, and not as dynamic tools for developing several simultaneous ideas (Deininger et al., 2017).

(2) Prototypes as social mediators

The social dimension of design learning is crucial. Collaborative designing includes productive thinking within interaction: it is both reflected in and stimulated by discourse between collaborators as they share, evaluate, and revise ideas to support the progress of their design process (Hennessy & Murphy, 1999; Kangas et al., 2013a; 2013b). Prototypes provide material anchors for design activity and interaction that focus on shared design efforts. Through materialization and model making, design ideas become visible for joint evaluation and development (Ramduny-Ellis et al., 2010) and help create a common ground for teams to understand (Lahti et al., 2016). Materials and model building could also affect the division of labor (Lahti et al., 2016). For example, Rowell (2002) has pointed out that possession of a particular tool could also give authority to the use of materials shaped by that tool. Working on the prototypes can help explicate and verbalize vague ideas, but also gestures such as pointing are used in collaborative designing. Gestures occurring when manipulating an artifact can be used to illustrate its functions and usage. Gestures also have a dynamic role in creating and shaping design ideas and stimulate further collaborative refinement of design ideas (Härkki et. al., 2018).

(3) Prototypes as material constraints and inspiration

Besides the material properties of the designed artifact, the design process is affected by the materials used for prototyping. For example, prototyping materials can condition later design decisions (Lahti et al., 2016; Tan, Keune, & Peppler. 2016) and inspire imagination and creativity at the beginning of the process (Alesina & Lupton, 2010; Heimdal & Rosenqvist, 2012). Material design constraints (Lawson, 1997) might, as Ramduny-Ellis et al. (2010) argue, prevent obvious solutions and encourage novel ideas. Furthermore, Ramduny-Ellis et al. (2010) emphasize that the possibilities relating to a certain material in a design task, such as prototyping, are dependent on the designers' past knowledge and skills. A lack of craft skills and, consequently, difficulties in materializing the idea can, according to Groth (2016), result in frustration towards the whole process. In elementary school, material prototyping requires craft skills and material knowledge. On the other hand, prototyping can itself offer pupils personal, embodied experiences of materials, which in turn allow them to build deep material knowledge (Härkki, Seitamaa-Hakkarainen, & Hakkarainen, 2016; Illum & Johansson, 2012). Material prototyping is a relatively slow process (Welch et al., 2000). However, Vrencoska (2013) argues that the slowness of material working can allow time for profound idea refinement. Clapp et al. (2016) state that the tangibility of material working can be engaging and stimulating, owing to, for example, the multisensorial qualities of physical materials (Jacucci and Wagner, 2007). While rich material resources can inspire imagination (Alesina & Lupton, 2010), a limited selection of materials can help pupils to focus on the task at hand (Clapp et al., 2016). On the whole, in addition to influencing the outcome of a design activity, material properties constrain and inspire the work of a designer (Lahti et al., 2016; Lawson, 1997; Ramduny-Ellis et al., 2010).

Method

Participants and the Context of the Study

The data for the present study were collected in a co-invention project that was organized in an elementary school in Helsinki, Finland. This was part of a larger research project in which pupils from several schools were engaged in investigative practices of learning that involved collaborative designing, inventing and constructing artifacts. In all schools, the projects were designed by teachers and researchers together, but the teachers were responsible for implementing the project. In the present study, the co-invention challenge assigned to the pupil teams was open-ended: to find a novel solution for an everyday problem. Three 5th grade classes (75 pupils aged 10 to 11 years) and four teachers participated (one craft teacher and three class teachers). The project involved eleven weekly co-design sessions of approximately 90 minutes each. Teachers worked as pairs: two class teachers (A and B) together and the craft teacher (C) with the class teacher (D). Pupils worked in small teams (3 to 5 pupils), developing their co-invention with the help of teachers, researchers and experts from outside the school.

During the ideation stage, pupils consulted parents, visited museums and met a professional inventor. Pupil teams built one or two physical 3D models of their invention with low-fidelity (low-fi) materials, such as plastic board, play dough and bubble wrap. The purpose of prototyping was to make a non-working model in order to facilitate the teams' work through materialization, and support them in presenting their invention. The classes worked on the design project mostly during their weekly craft lessons. They used the schools' technology education classroom, where the materials and equipment were stored, and their own classrooms and computer labs. The project started with ideation in fall 2016. The teams were formed with teacher support according to pupils' interests. During spring 2017, teams refined their ideas, built the prototype, visited a design museum, and participated in an app-developing workshop. Pupil teams presented their inventions to their classmates and teachers at the school. Some of the teams also participated in an "invention fair" organized at the University of Helsinki. Table 1 presents the spring 2017 project timeline.

Table 1. The timeline of the invention project

2017: January	February	March	April	May
Ideation				
	Prototyping			
		Presentation preparation		
			Museum visit	
			Presentation at school	
				App workshop
				Invention fair

The pupil teams produced various inventions, for example, to facilitate cleaning, division of housework, organization of belongings, and studying. Most of the inventions included essential digital elements, which were modeled with the low-fi materials. Of the 20 teams, we selected three to be closely followed by video recording. We limited the number of observed teams to three for practical reasons, since our aim was to conduct a fine-grained analysis. We selected varying teams. These teams differed in size, gender, and the nature of invention, and were named after their inventions: Kamlele, the Technical Cleaner, and the Multipurpose Chair. The teams' prototypes are illustrated in Figure 1.

Figure 1. From left to right, Kamlele, the Technical Cleaner, and the Multipurpose Chair

Kamlele reminds the user of household chores. The device can be placed, for example, on a dishwasher or on a dog's collar. The personalized ringing tone announces whose turn it is to complete the chore. The device comes in multiple sizes and the color adapts to home decor. The team consisted of five girls. Their teachers were the two class teachers (A and B).

The *Technical Cleaner* facilitates cleaning. For example, it takes pictures of the home, evaluates how messy and dusty it is, and reminds the user to clean up. Group consisted of five members: three boys and two girls. Their teachers were the two class teachers (A and B).

The *Multipurpose Chair* makes studying at school easier. The chair has a sound-isolating hood, which can be lowered when needed. The group consisted of three boys. Their teachers were the craft teacher (C) and one of the class teachers (D).

Data collection and analysis

The design sessions of the selected teams were recorded with two GoPro-cameras: one hanging from the ceiling, and other placed on a tripod, in order to document pupils' gestures and material manipulation during their design activities. In addition, photos of sketches and prototypes were taken after each session. In this study, we focused on sessions where the main design activity was prototyping. Pupils made some finishing touches to the prototypes after the selected sessions, but the basic idea did not evolve significantly. For the analysis, we chose two sessions from each team: a total of six sessions of 90 minutes each. During these six recordings, a wide variety of prototyping actions appeared.

In order to create systematic and focused analysis of the rich video data, we adapted Ash's (2007) methodology of three different levels: macro, intermediate, and micro. The macro-level analysis aimed at creating a flow chart of all design activities. We coded the video recordings in 3-minute segments with the ELAN multimedia annotator. The theory-driven coding template was developed for characterizing the collaborative design and making processes. This template was developed for the larger research project, and used for all video data of the project (Riikonen, Seitamaa-Hakkarainen, & Hakkarainen, 2018). The coding template and codes focused on a) the main verbal actions (for example, seeking information, process organizing, ideation, evaluation, redefining the idea); b) embodied actions (i.e., drawing, model making, material experimentation); c) non-task-related action; d) nature of collaboration within the teams. Due to the iterative and cyclical nature of a design process, different phases of ideation and idea refinement appeared simultaneously with prototyping. The coding process ensured systematic management of the video data, and the visual process rug (figure 2) provided a brief representation of the design sessions, as well as context for more detailed levels of analysis. The process rug, together with multiple viewings of the video data, informed the next, intermediate level of analysis, which focused on choosing and describing "significant events."

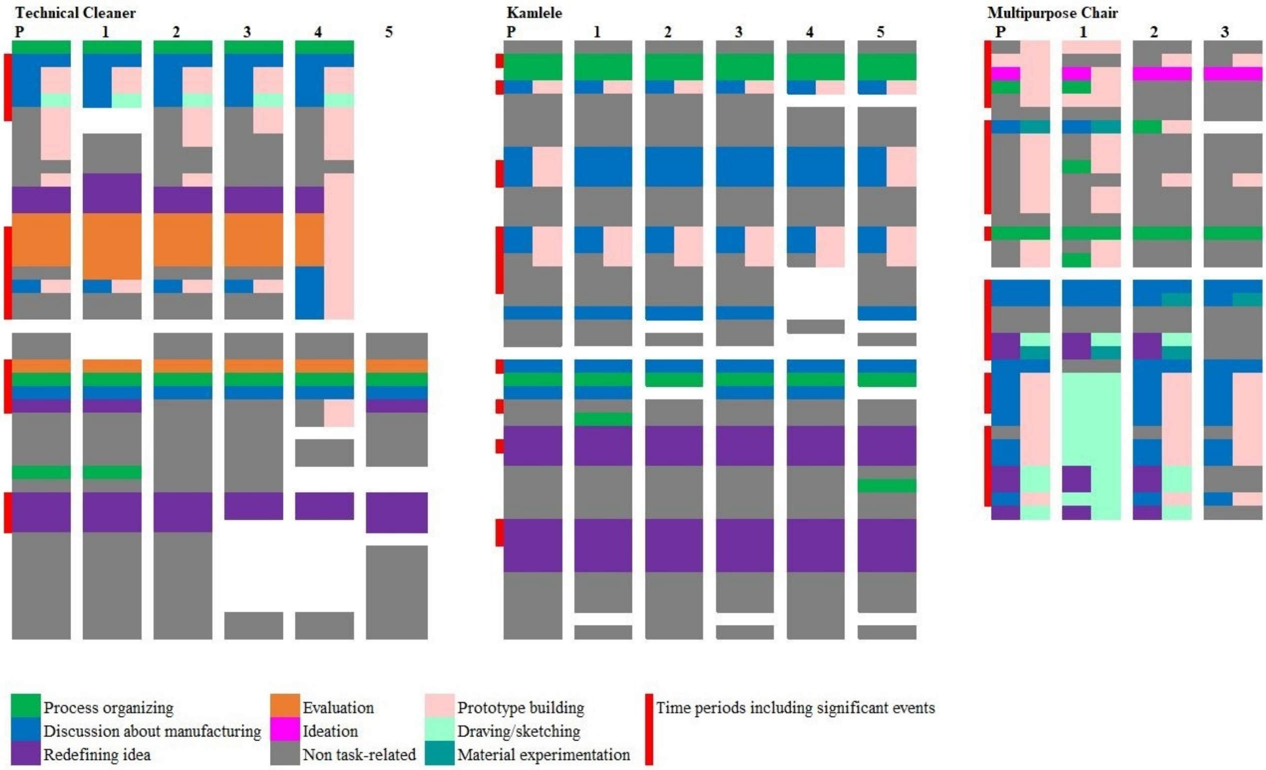

Figure 2. Process rugs of the two sessions. P = teams' primary design actions, 1...n = actions of individual team members

In the present study, significant events presented prototyping actions, such as a team member explaining his/her idea to others while using the prototype as a representation. Figure 2 presents the design activities of the prototyping sessions of each team, and the time periods where the prototype appeared significantly (red columns in figure 2). Besides building, pupils used the prototype during process organization, discussions about manufacturing, evaluation, and refinement of the idea. The intermediate level analysis was divided into two phases: identifying all significant events and then selecting representative events for micro-level analysis. We identified 41 significant events according to the following criteria:

(1) The event had a clear beginning and ending
(2) The event was continuous
(3) The event included some of the following embodied or verbal prototyping actions:
a) prototype was used during ideation,
b) prototype appeared as a social mediator,
c) prototype emerged as a material constraint

The first two criteria directly follow Ash's (2007) methodology; the third criterion was based on the theoretical background of the study. A time period including significant events (Figure 2), often comprised multiple successive events, each presenting different prototyping roles. The 41 significant events identified lasted from 20 seconds to a few minutes. The length of a significant event was not bound to the three-minute segments but followed the natural duration of the event itself, according to the first two criteria described above. We wrote a short description of each significant event and selected 16 events for the micro-level analysis. These events represented the three perspectives of the third criterion described above: prototype appearing in ideation, as a social mediator, and as a constraint. When similar prototyping actions recurred in multiple significant events, we chose only one or two representative examples and excluded the other events.

The micro-level analysis of the 16 events focused on details such as gestures, material manipulation, and verbalization of ideas. We created transcripts including verbal dialogue and rough descriptions of simultaneous embodied actions. The transcripts were analyzed alongside the video clips to ensure that the diversity of embodiment would not be lost in the limitations of verbal description. We categorized different types of actions under two foci that emerged from the data. Focus was either on actions related to ideation, or actions related to working. The foci were further classified into various categories. Table 2 presents the perspectives, foci and categories of intermediate and micro level of analyses.

Table 2. The perspectives, foci, and categories of intermediate and micro-level analyses

Perspectives	Foci	Categories
Prototype as an aid for thinking	Ideation: Idea refinement	Evaluating the physical representation of the idea Material experiments for refining structures Prototype involved in ideation conversation
	Working: Prototype refinement	Prototype-building practicalities Choices based on material feedback
Prototype as social mediator	Ideation: Idea verbalization	Presentation of existing idea
	Working: Teamwork	Division of labor Prototype as a focal point
Prototype as material constraint and inspiration	Ideation: Design constraints	Material design constraints
	Working: Material practicalities	Playing around Slow progress Rough appearance

In this study, the three levels together offer a comprehensive overview of the roles of prototyping in elementary students' collaborative designing. We used the levels to provide different viewpoints: when (macro), what (intermediate), and how (micro). For example, a prototype appears during ideation conversation (macro) as a support for verbalizing an idea (intermediate), during which a pupil points to the prototype, and manipulates it to demonstrate a vague verbal expression "like this" (micro). In the following, the findings presented are mainly related to the micro-level of analysis, however, the macro- and intermediate-levels provided a broader context for the detailed description of activities.

Findings

Prototypes as aids for thinking

Prototypes appeared as aids for thinking while the pupils were either refining their ideas or the prototype itself. Idea refinement included evaluation of the physical representation of the idea, material experiments for refining structures, and prototype involved in ideation conversation. Prototype refinement included prototype-building issues and choices that were made based on material feedback.

All teams refined their ideas by evaluating the prototype, which acted as a physical representation of the design idea. Kamlele and Technical Cleaner groups built box-shaped prototypes. The Technical Cleaner group's prototype shape was based on a sketch that the team drew without accurate three dimensional measurements. The size and dimensions of the prototype surprised the pupils, and they commented that the prototype did not look like it was supposed to. The team decided that the final artifact should be wider and thinner. These concrete suggestions for refining the shape of their invention were based on evaluating the prototype.

Prototypes were actively present in the conversations featuring collaborative ideation. When the Kamlele group was ideating how the invention could be attached to household items, they shared their ideas while interacting with the prototype using gestures and words. For example, pupils pointed at the planned place of the attachment method (Figure 3); lifted the prototype against the wall to enact the positioning of the device; and demonstrated missing elements, such as hooks or suction cups, with gestures.

Extract 1.

Caroline [*grabs the prototype*]: I was thinking [*points to a side of the prototype*] that it could be like this here…like this would be entirely magnetic.
[*Points towards the table and twirls her finger*] Then there would be a small bag where there would be, for example, four suction cups.
[*Forms a cup with her hands and takes her hands to the prototype. Taps the imagined point of attachment with her finger*] And then on the other side of the suction cups, there would be another magnet, and then those could be like fastened there.

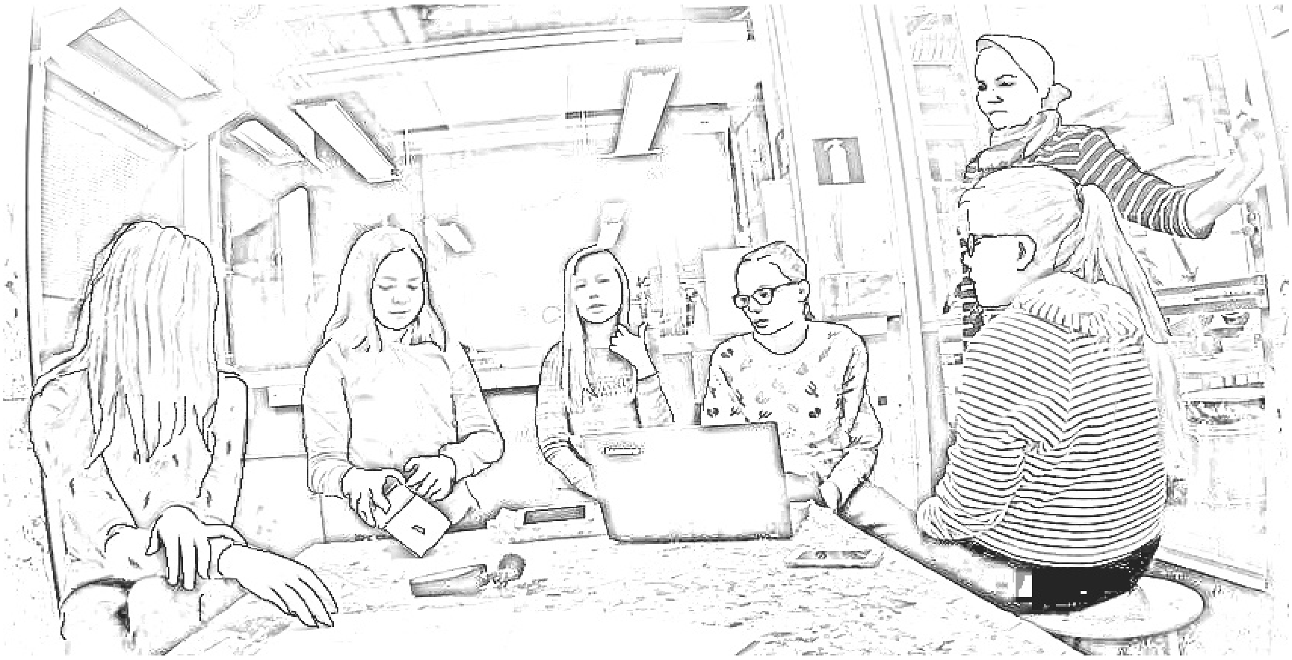

Figure 3. A Kamlele pupil pointing to the prototype during one of the team's ideation

The Technical Cleaner group was interacting with the prototype while ideating the digital features of the artifact. The teacher asked about the function of a certain piece in the prototype, and the team first told him that it served just for aesthetic purposes. But during the conversation, which involved gesturing to the prototype and passing the prototype around, they came up with a new idea: the piece in question could be a display with digital functions. Hence, verbalization of ideas appeared simultaneously with ideation.

The prototype of the Multipurpose Chair had some mechanical structures, such as its folding hood. A pupil had built a small prototype of the hood; when evaluating it with the teacher, the team agreed that some changes needed to be made. First the pupil, by himself, silently and slowly moved his finger across the prototype. Then, he unraveled the prototype and started to build the new hood. He took one piece at a time in his hands, twisted and turned it, tested different ways to place it, then glued the piece in. The mechanics of the new hood was based on the teacher's vague suggestion, but the pupil found the exact solution through material manipulation. Later, another pupil from the Multipurpose Chair group came up with the idea of a foldable leg rest when absent-mindedly twisting a play dough model of the chair. In these situations, the embodied thinking, ideation, and manipulation of materials appeared simultaneously.

The teams' main focus in the selected design sessions was prototype building. The issues relating to the prototype were discussed more than those relating to the designed artifact. Teams used physical materials for testing the structures of the prototype before making decisions and decided measurements with materials. For example, pupils from the Kamlele and Multipurpose Chair groups manipulated the pieces of their prototype and tried to construct them in different ways before gluing them together. A pupil from the Technical Cleaner group determined the size of a camera based on material manipulation. She took some play dough in her hand, looked at it, and then added some more play dough. Next, the team decided the size of their prototype by placing the play dough camera on a plastic board and drawing a rectangle around it. None of the three teams made detailed plans for building the prototype. Instead, when a problem occurred during building, pupils rather used immediate material feedback to solve it.

Prototypes as social mediators

Prototypes appeared as social mediators to support pupils' teamwork and the verbalization of their ideas. During ideation, the prototypes were used for verbalization of existing ideas. During teamwork, the prototype was involved in the division of labor and acted as a focal point.

When pupils presented their existing ideas to others, they used the prototype as an aid for verbalization. For example, a pupil from the Multipurpose Chair group presented their idea to a teacher with words like "this way," "here," "like that." However, he supported those vague expressions by gesturing to the prototype and manipulating it. The Technical Cleaner group used their low-fi prototype for presenting digital ideas to the teacher. They pointed to the prototype when explaining planned digital functions. In the Multipurpose Chair group, one pupil said he did not understand the team's idea well enough to participate in the construction. The two other pupils utilized a sketch and a prototype as aids for explaining their idea (Figure 4). Pupils pointed to the sketch and then to the comparable structure of the prototype, manipulated the prototype, and referred to the prototype with verbal expressions. Here, the prototype assisted in creating a common ground for the teams' understanding of their idea in development.

Extract 2.

David [*Points at the sketch*]: Look, there is the chair, here are the retainers
John [*Comes along. Points at the sketch.*]: Look. Here is the bottom of the chair, this is the chair itself. Look, it is…. Where is the actual prototype? Here! [*Reaches for prototype.*]
Michael: Is it a little like a sun... umm, sun thing…
John [*Points at the sketch and the prototype in turn.*]: Look, these are like this part. This is this part. This is the bottom thing. [*Draws with his finger on the prototype.*] And then it has this hood on top. [*Grabs the hood and sets it on top of the chair.*]
Michael: Yeah, I get it

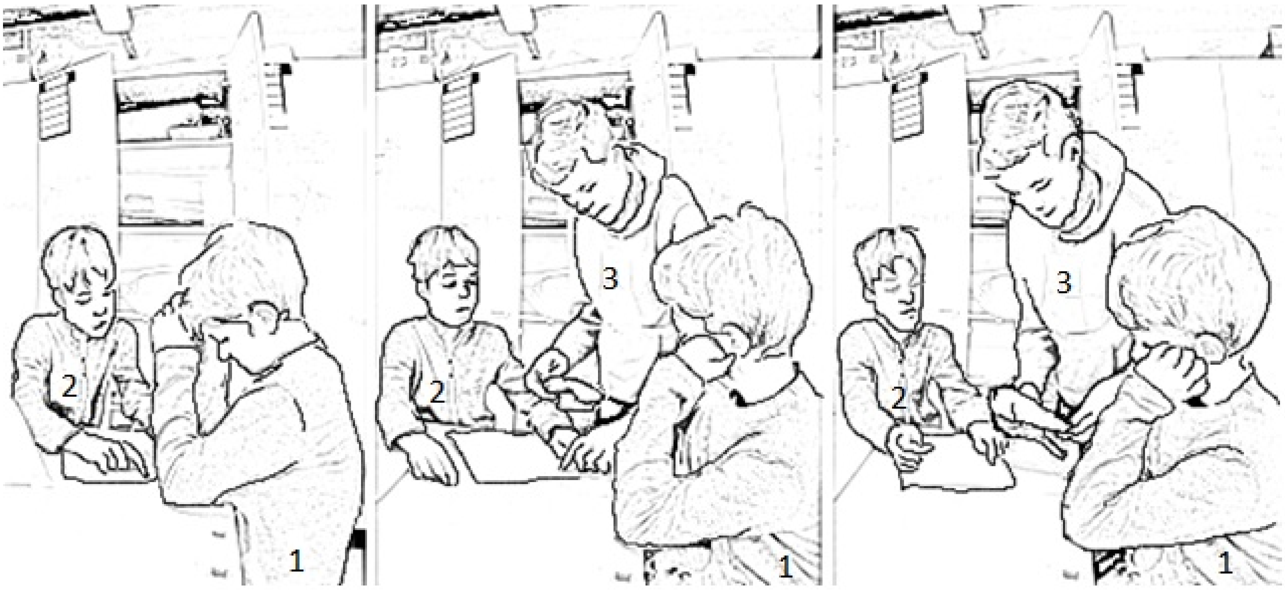

Figure 4. Multipurpose Chair pupils (David (2) and John (3)) explaining their idea to a team member (Michael (1)) with a sketch and a prototype

In many cases, the prototype was a focal point for the team. For example, a pupil in the Kamlele group was building the prototype and others were talking about off-task topics. But when the pieces of the prototype did not seem to fit together, everyone turned their attention to the prototype. The team started to consider possible solutions together, and when one pupil presented her idea, she simultaneously demonstrated it with the prototype. In some cases, team members also used the prototype to emphasize their turn to speak. For example, when a pupil in the Technical Cleaner group wanted to present his idea, he took the prototype and waved it in the air demanding attention. When he finally got the floor, he presented the idea by drawing an imaginary display with his finger on the prototype. Similarly, when the Kamlele group was ideating the attachment method together with the teacher, the pupil who wanted to speak snatched the prototype for herself.

An uneven division of labor occurred in all the groups. Often, only one pupil was building the prototype while others were playing around or doing some off-task actions. For example, in the Multipurpose Chair group, one of the pupils was building the prototype by himself, and also developing the idea alone. When other pupils asked for something to do, they got only some assisting jobs, for example, to bring some materials or make the glue gun ready. Also, in Technical Cleaner group one pupil took the main responsibility for building the prototype. Nonetheless, unlike in the Multipurpose Chair group, all members of the Technical Cleaner group participated on ideation during prototyping. Pupils followed the construction process closely, commented on the pivotal phases, and suggested solutions. Collaboration occurred even when there were not enough tasks for everyone in building of the simple prototype

However, from time to time teams did find ways to engage everyone in the construction. During those moments, the construction task was divided into smaller tasks. For example, the Technical Cleaner group divided the labor between four pupils, so that one pupil made the buttons from play dough, two pupils cut walls from foam board, and one pupil wrote the presentation on the computer. The division of labor was not decided verbally, but by taking control of the equipment or materials needed for a task. Even when pupils had their own tasks, they did not work in isolation but commented on each other’s work. For example, the whole Technical Cleaner group reflected together on how they could draw a rectangle with a single ruler. The material issues of the prototype created possibilities for combining the divided work.

Prototypes as material constraints and inspiration

Prototypes as material constraints appeared in the design process when pupils evaluated design constraints related to materiality. Material constraints also appeared in practicalities, for example through the slow progression of work or rough appearance of a prototype.

Prototypes can be used for evaluating the material constraints of the designed artifact. However, in this study, teams discussed material constraints only twice. For example, two pupils in the Multipurpose Chair group reflected on the footrest of the chair. One team member suggested that the rest could come out from under the chair. By testing the suggestion with the prototype, the other pupil concluded that there was not enough space. Similarly, Technical Cleaner group had decided that the artifact should be thinner, but one pupil questioned whether the planned display would fit in the thinner device. A pupil then tested the size of the display on the prototype with gestures (Figure 5).

Extract 3.

Ted: So, how will the display fit in there, if…
Stina [*Lifts the prototype and sets her hand in the middle of the prototype*.]: Then it comes to… Because now there is only this much. So it will fit. [*Demonstrates the size of an imaginary display with her fingers and moves them upwards*] If we take half off, then this only moves up there and it is its… [*Moves her finger across the prototype*] And it can in this order, that time, place…
Ted: Yeah

Figure 5. A member of the Technical Cleaner team demonstrating the size of a planned display in relation to the prototype

Material qualities of the prototype affected the work; pupils played around with materials and made sensory observations. In this study, these observations focused on the prototype, not on the materials of the designed artifact. For example, the Technical Cleaner group marveled at the smell and stickiness of play dough, a material solely used for prototyping. A pupil in the Kamlele group sanded a piece of plastic board, a prototyping material, and noticed that the piece heated up. The whole team got excited and everyone wanted to try the hot plastic board themselves. Moreover, off-task playing with the materials occurred, for instance, when pupils built funny figurines from play dough, made a smartphone appear to be broken with stripes of hot glue, and found different ways to twirl bubble wrap around a finger. Materials invited pupils to play and inquire, but, here, this excitement was not notably task-related.

The slow progress puzzled pupils. During these recorded sessions, all three teams commented on how little they had managed to accomplish. As the process rug (figure 2) demonstrates, especially the second design session of Technical cleaner and Kamlele teams included plenty of off-task activities. Teams did not use materials requiring slow craft techniques. Two of the teams even built a very simple prototype: a box. Yet, one reason for slowness appeared to be that the pupils did not have enough craft skills to manipulate the materials or to use the tools. For instance, the Kamlele group had to wait for the teacher for a long while when the glue gun was not working. In the Multipurpose Chair group, two pupils had trouble sawing a board, and were just about to quit altogether, when a teacher arrived to provide an example. At this stage, manipulating the materials, the teachers' support was essential to the teams' progress.

The appearance of the prototypes in this study was rather rough. Pupils reacted to the appearance with laughter. They bemoaned: "that looks stupid," "this looks like a washing machine," "yuck" and "that is so ugly." The Multipurpose Chair group was the only team that built a second, more attractive, version of their prototype. In their case, even the teacher commented that the first version was ugly. The pupils evaluated the second version as a "bit weird but OK." In the Multipurpose Chair group, one of the pupils made a virtual model of the chair. All conversations about the virtual model concerned the appearance of the chair, which the team members admired the in the virtual model. Their material prototype focused more on the structure and mechanics of the artifact.

Discussion

In the present study, we investigated the role of prototyping and material model making in elementary school pupils' collaborative design process. We examined how the prototypes were used as an aid for thinking or as social mediators, and how they functioned both as constraints and inspiration in the process. In this section, we present opportunities and challenges related to the three perspectives, as well as provide concluding remarks.

The prototypes were used as *aids for thinking*, mainly for refining the prototype itself but also for developing the design ideas. The teams used the prototype for evaluating features of the artifact, which supported pupils in making concrete refinement suggestions. For instance, the Kamlele and Technical Cleaner groups focused on the shape and size of the artifact; pupils compared the prototype to their original idea and presented some concrete suggestions for refining the shape. The Multipurpose Chair group used the prototype for evaluating the structure and structural functions of the artifact, testing their ideas by manipulating the prototype. In the present study, the teams discussed more the practical issues concerning the prototype than, for example, the material design constraints of the designed artifact. Previous studies (e.g. Kangas et al., 2013a; Looijenga, Kalpwijk & De Vries, 2015; Welch, 1998) have shown that a concrete and tangible prototype can aid elementary school pupils in evaluating their ideas. Furthermore, embodied thinking (e.g. Groth, 2017) was revealed while pupils were working with the prototype. They tested structural options before gluing the prototype together. During collaborative ideation, the prototype was indicated and "expanded" with gestures.

The three-dimensional prototype aided pupils in perceiving the shape and dimensions of the artifact; mere two-dimensional sketches had not provided them with adequate understanding of the three-dimensional shape. For example, the Technical Cleaner team was surprised by the shape of their prototype, after building it according to a two-dimensional sketch. Kangas et al. (2013b) have discovered similar benefits of three-dimensional prototyping. Williams and Sutton (2011) emphasized the importance of spatial reasoning for adult designers, including the ability to imagine 3D shapes from a 2D presentation. Furthermore, pupils should learn how to plan, model, test and iterate solutions by moving repeatedly between 2D and 3D models. These iterations would inspire mental visualization and support spatial skills (Riley, 2016, 21).

When verbalizing abstract ideas and presenting their plans, pupils used the prototype as *a social mediator*. When new ideas were proposed, old ideas were refined, or the existing idea was presented, pupils referred to the prototype with words and gestures, such as pointing. Illum and Johansson (2012) have emphasized that material representation supports the verbalization of abstract ideas (see also Kangas, 2013a; 2013b; Welch, 1998). In this study, the prototype also supported the collaboration by gathering attention. Pupils utilized the prototype when they wanted everyone to listen: they snatched the prototype or waved it around. Rowell (2002) pointed out that physical materials stimulate collaboration. In this study, practical issues with building demanded collaboration: when a problem occurred, groups' diffused attention came to focus on the prototype

In the present study, the division of work between team members was often uneven. Pupils did not find prototype-building tasks for everybody, so some pupils spent a major part of the sessions idle, engaging in actions unrelated to the task. For example, in the Multipurpose Chair group only one pupil took the lead, and two others were left somewhat as outsiders. Two other groups aimed to divide the work more evenly by dividing the building project into smaller tasks; however, this was not always possible because of the simplicity of the prototype. Clapp et al. (2016) emphasized the importance of participation in collaboration. They also posit the view that a limited amount of materials might result in pupils having to consider, for example, sharing and other practical aspects of collaboration.

The prototypes also acted as *constraints and inspiration to the process*. Young pupils do not have the same fine motor skills, material knowledge, and craft skills as adults. In this study, the lack of these skills appeared as challenges in simple building tasks. Pupils seemed to get frustrated with the slowness of the work. They commented on what little progress they made during the sessions. Welch (2000) described material prototyping as naturally slower than sketching. The slowness of physical prototypes has been pointed out in studies in industrial design (Ramduny-Ellis, 2010) and design studies (Vrencoska, 2013). In this study, pupils found it challenging to work with even simple materials and tools. These challenges alongside the uneven division of labor probably accounted for some of the slow progress. Materials and techniques used for the prototype were simple and basic, and so were the pupils' craft skills. As a result, the appearance of the prototype was rough. The appearance provoked laughs and headshakes among the pupils and even a teacher. Pupils said out loud that the prototype does not look the way it should. Without the technical skills to manipulate materials into the desired form, it is difficult to materialize an idea. Groth (2016) emphasized that even among adult designers insufficient skills in material manipulation can result in frustration throughout the entire design process.

Welch (1998) pointed out that children have natural experience with building and designing through play. Concrete materials could stimulate playfulness: in this study pupils played with the materials but the play was usually not task related. Nevertheless, pupils were visibly excited by the heat created by sandpaper, the gooey feel of the modelling clay or the funny little figures they made with play dough. Steering this enthusiasm for play towards the task at hand is a question that should be noted in elementary school design teaching.

To conclude, we can say that the material prototype had a rich and versatile role in the collaborative design process. The prototype was in active use when pupils were building it, but also during process organization, discussions about manufacturing, ideation conversations, evaluation, and refinement of the idea. In this study, some characteristic features of prototyping in elementary school appeared. These include young pupils' skills in spatial reasoning and craft techniques, and their tendency towards playfulness. The prototype was instrumental in collaboration and it was used for supporting the verbalization and refinement of ideas. The prototype was also used for testing the structure of the artifact and it aided pupils in determining its three-dimensional shape and dimensions. However, some challenges in working with the prototype also appeared. The work was slow, the division of labor uneven, and the appearance of the prototype was mainly just amusing. Nevertheless, this study suggests that prototyping has potential in elementary school projects.

Conclusions

The findings of the present study provide grounds for the pedagogical and theoretical implications of the role of prototyping in elementary students' collaborative design process.

Building a material representation of an idea is a broad task. Binder et al. (2011) argued that a prototype can focus on several details and have multiple goals, and that professional designers usually create several contemporaneous prototypes. It is no surprise that elementary school pupils might have difficulties comprehending the purpose of the prototype. According to Klapwijk and Rodewijk (2018), even though young pupils often need teachers' support in selecting the prototyping goal, pupils can learn to develop specific sub-goals for their prototype building. In the present study, the prototyping task did not have a specific goal and it became evident that while building the prototype, pupils' attention and design actions focused mainly on the prototype itself and not on developing their design ideas.

Also, time was an issue in the present study. Pupils tried to build their whole idea in a relevantly short time period with limited resources and skills. Constraining the task could help pupils to focus on only selected, relevant questions, relating to, for example shape, mechanical function, or appearance. Klapwijk and Rodewijk (2018) emphasize the importance of very specific prototyping goals, in order to help pupils to ignore other, currently irrelevant, goals. Also, focusing on some details could give time for iteration. Clapp et al. (2016) emphasized the importance of iteration for refinement of the idea (see also Looijenga et al., 2015; Welch, 1998). In this study, only the

Multipurpose Chair group had time to build a second version of their prototype. Other groups also had refinement ideas, but they did not have time for iteration.

Young pupils do not necessarily comprehend the range of possibilities that the prototype offers, as expert designers do. Kangas et al. (2013a) stated that the prototype can easily take on a more dominant role than the designed artifact in elementary school settings, as was the case in the present study. Therefore, the role of the prototype as a tool should be made explicit. Adult designer utilize the prototype, for instace, for testing structural or visual details (Binder et al., 2011) or by visualizing the idea when presenting it (Ramduny-Ellis et al., 2010). Similarly, Binder et al. (2011) have pointed out that the main focus of designing should be on the designed artifact, and the prototype is merely a medium for connecting with the artifact.

Physical materials bring along practical issues. Clapp et al. (2016) pointed out that prototyping with physical materials can be messy and complex; consequently, it is especially important to pay attention to the organization of the materials and the classroom. Prototyping and, therefore, the whole design process in this study was occasionally hindered because of practical issues, such as missing tape or a broken glue gun. Another practical challenge was the young pupils' lack of craft skills. In this study, teachers chose simple materials and simple techniques. On the other hand, Clapp et al. (2016) argued that high quality materials and professional tools could be important for learning and motivation. Finding motivating high quality materials and techniques that suit the skills of the pupils requires craft experience and material knowledge from the teacher. Ramduny-Ellis (2010) argued that the possibilities of the material are more dependent on the skills of the user than on the choice of the material. In an elementary school setting, teachers' ideas and examples could fill the gaps in pupils' skills. Craft skills could also be taught either beforehand or during the process by, for example, peer-to-peer tutoring.

To conclude, material prototyping needs some special attention from the teacher, when designing the task and planning the project. Clear goals and a reasonable level of constraint could help focus attention on the designed artifact and avert attention from irrelevant qualities of the prototype. Practical issues need to be considered in order to make prototyping sessions flow smoothly. Pupils craft skills should be noted when designing the task and choosing the materials.

Further research is needed in order to implement the tentative results of this study in practice. To gain a more profound understanding of the phenomenon, various projects led by different teachers with a wide age-range of pupils should be studied. An interesting next step for study could be an investigation into how to bridge the gap between modern digital technologies and traditional craft techniques. In this study, small glimpses of simultaneous development of material and digital prototype appeared: material prototype modelled structures and digital prototype presented aesthetics. When studying the possibilities of digital prototyping, the unique qualities of materiality should not be forgotten.

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