Design Thinking in Elementary Students' Collaborative Lamp Designing Process

Kaiju Kangas, University of Helsinki, Finland

Pirita Seitamaa-Hakkarainen, University of Helsinki, Finland

Kai Hakkarainen, University of Turku, Finland

Abstract
Design and Technology education is potentially a rich environment for successful learning, if the management of the whole design process is emphasised, and students' design thinking is promoted. The aim of the present study was to unfold the collaborative design process of one team of elementary students, in order to understand their multimodal ways of design thinking. The videotaped design episodes of the team constitute the data source of the study. CORDTRA diagrams were used for opening up the design process, providing means to analyse the complex and iterative process in a structured manner. The results indicate that the students' design thinking was collaborative, materially mediated, and embodied in nature. Engaging in various concrete and material, as well as epistemic and conceptual activities provided the students with opportunities to learn the foundational design skills. Further, the multifaceted design process integrated skills needed for learning also something other than design.

Key words
design thinking, collaborative designing, embodied thinking, CORDTRA diagrams

Introduction
The goal of Design and Technology (D&T) education has long been to create critical understanding of design practice both through action and reflection upon it (Roth, 2001; Schön, 1983). These practices include production of design artefacts, such as sketches, models and final products, which provide mediating entry into design discourse (Rowell, 2004). However, in basic education, the construction of these artefacts is often perceived as the primary focus of learning activities, rather than as a way of supporting the rationale directing the design practice. The epistemic richness of the practice is reduced (Schwartz et al., 2009) if the students are not provided with opportunities to recognise, create, and reflect on their own ways of participating in the design culture (Murphy and Hennessy, 2001; Rowell, 2004). Production of visual and material artefacts is a crucial element of success in the design field, which depends on the management of the whole design process in all its components, from idea generation to the mastery of techniques. Students need to manage the procedures of planning and making, integrating representations of mind to surrounding material/physical and societal conditions, reflecting possibilities, and testing the boundaries of self-fulfilment. Learning through designing arguably has an essential role in human development by facilitating the development of cognitive, spatial, motor, social, and aesthetic skills.

Designing puts emphasis on conceiving something new and clarifying as yet unknown details. This requires active knowledge creation and meaning making-aspects which make D&T settings potentially rich environments for successful learning. Design thinking has the potential to promote, for example, constructive thinking, creative problem-solving, collaboration, and multimodality (Cross, 2006; Kolodner et al., 2003). According to Sawyer (2012), many principles of the schools of art and design are closely aligned with learning sciences findings, yet provide a different vision of teaching and learning. Moreover, in collaborative design activity, students share a task around an actual, concrete artefact, which becomes an object of their shared cognition (Medway, 1996). Design discourse, including sketching, modelling, and interactions with objects, has the unique potential to support shared thinking processes (Murphy and Hennessy, 2001). In recent years, the embodied dimension of designers' and artisans' work has gained increasing attention (Keller and Keller, 1996; Patel, 2008). Research on embodied cognition questions the traditional dualism of body and mind, and emphasises the role of the body, handling of tools and materials, use of space, and interaction with others in the thinking processes (for review, see Hall and Nemirowsky, 2011).

The present study introduces elementary students' collaborative lamp designing process, where professional designing, multimodality, and critical understanding of the design practice were deliberately fostered. Leadership of the project was provided by a professional designer, who was present in the classroom together with the teacher. In the following, we will first briefly discuss design thinking and the role of mediation in the design process. Then, we will introduce our empirical study and the method of using

CORDTRA (*Chronologically-Oriented Representations of Discourse and Tool-Related Activity*, Hmelo-Silver, 2003; Hmelo-Silver et al., 2008; 2009; 2011) diagrams for opening up the design process, chronologically and visually. Our goal was to unfold the design process of one student team in order to shed light on elementary students' multimodal ways of design thinking. We addressed the following research questions:

1. What was the nature of elementary students' collaborative design thinking?
2. How did the design artefacts used during the process mediate the students' design thinking?
3. What role did embodied thinking play during the process?

Design Thinking

The term Design Thinking is complex, emergent, and diverse in both its construction and application. According to Stewart (2011) the approaches and techniques that have been associated with design thinking include tacit processes of professionals in established design disciplines and emerging design scenarios and practices. Design is seen as interpretive practice within which particular kinds of sense-making are operative. Designers have abilities for rapid evaluation of complex contexts and for iterative projection of promising possibilities, i.e., promisingness that is related to expertise and creativity (Bereiter and Scardamalia, 1993). Design thinking is situated in nature, and designers have the capacity to respond to particularity, to engage in an iterative dialogue with the design situation, and to recognize which of the possibilities that emerge from the dialogue are most suitable (Stewart, 2011). Designing can be conceptualised as a process, a quest for something new, something that does not yet exist.

Designing has also been characterised as a dual-space search within two problem spaces: the composition space representing visual design, and the construction space representing technical design (Seitamaa-Hakkarainen and Hakkarainen, 2001). Composition space consists of the organisation of the visual elements and principles, such as shape, pattern and colour, selected and manipulated during design process. Construction space is seen as organisation and manipulation of technical elements and principles, such as structure, material, and production methods. Designing is moving within and between these spaces both horizontally, i.e., generating several, parallel ideas, and vertically, i.e., developing the ideas further and to a more detailed level (Seitamaa-Hakkarainen and Hakkarainen, 2004; see also Goel, 1995). Furthermore, there is a set of features, the design constraints, which determine and limit the design problem space (Goel and Pirolli, 1992; Goel, 1995; Seitamaa-Hakkarainen and Hakkarainen, 2001). Design constraints have a central role in the design process, through them a designer is able to construct a rationale for design decisions. Dealing with the multifaceted nature of design spaces is often based on teamwork combining variety of knowledge and skills.

Consequently, the use of collaborative settings, especially one involving peer collaboration, in the area of D&T education has increased. In D&T contexts, successful peer collaboration is a process in which students actively work together in creating and sharing their design ideas, deliberately making joint decisions and producing shared design objects, constructing and modifying their design solutions, as well as evaluating their outcomes through discourse (Hennessy and Murphy, 1999; Rowell, 2002). Genuine collaboration depends on the actors truly sharing the same object, as opposed to organising their common efforts by merely coordinating their joint activities (Lahti, Seitamaa-Hakkarainen, and Hakkarainen, 2004). The development and maintenance of the shared thought process is a central element in peer collaboration (Azmitia, 1988; Teasley and Roschelle, 1993); it is a reciprocal process of elaborating on each other's reasoning and viewpoints in order to construct a shared understanding of the task (Goos, Galbraith, and Renshaw, 2002). Three aspects have been proposed to define good collaboration: mutuality, joint focus of attention, and shared task alignment. 'Mutuality' refers to reciprocity with potential for all participants to meaningfully contribute; 'joint attention', to the degree which attention is focused by all, working in concert; and 'shared task alignment', the establishment of a collaborative orientation toward problem solving (Barron, 2000).

Mediators of Design Thinking

A central aspect of the design process is to conceptualise and visualise an idea of the emerging product; externalisation and visualisation help intangible ideas to become concrete and allow them to be generated, modified and transmitted between people (Goel, 1995; Lawson, 1997). Professional design activities rely on the use of various tools and design representations, such as sketches and notes (Al-Doy and Evans, 2011; Goel, 1995). In the context of D&T education, the interaction with two- and three-dimensional models (sketches, prototypes) offers students direct possibilities to explore and evaluate a proposed solution's form and function. Involving students in modelling practices can help them build domain expertise, epistemological understanding, and skills to create and evaluate knowledge (Schwartz et al., 2009).

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A review of the research examining the role of sketching for design professionals (Welch et al., 2000) shows that sketching has a crucial role in generating, developing, and communicating ideas; it is both a powerful form of thinking and the fundamental language of design (see also Seitamaa-Hakkarainen and Hakkarainen, 2004). Consequently, sketching is seen as central to developing capability in D&T education. It can be used to communicate design ideas with others; it also enables those others to contribute to the ideas (Al-Doy and Evans, 2011; Welch et al., 2000). In other words, various design representations allow students to interact with one another through the design object itself, as collaborating participants' activities are mediated and made visible through them. However, research has shown that novice designers rarely use two-dimensional models, i.e., sketching, but tend to move immediately to three-dimensional modelling (Welch, 1998). The formal design representations can become prioritised at the expense of participation and learning (Murphy and Hennessy, 2001), when the purpose and advantages of using them as design tools is not understood (Hope, 2005). Therefore, students should be explicitly taught the role of representations for developing design ideas. Hope (2000; 2005) has created a metaphor of drawing as both "a Container for ideas" and "a Journey on which to develop them" (2005, p. 45) for explaining the function of design drawing to elementary aged children. In project based on this kind of approach, children produce more than one design idea, carefully evaluate them, and either discard or develop them further through more drawings. Several related ideas, styles, and construction methods are constructed and combined. Understanding of a drawing as a design tool helps set children free from a felt necessity of having to produce any particular kind of drawing.

Design activities are fundamentally creative in nature, requiring implementation of conceptual ideas in design of materially embodied artefacts (Keller and Keller, 1996). The art, craft, and design processes involve parallel working through conceptual reflection and material experimentation and implementation. The creative process is, in itself, multi-modal: Conceptual, practical, and materially embodied activities cross-fertilise and support one another. Patel (2008) has created the concept of *embodied thinking*, which emphasises the role of the body in the process of thinking, i.e., how bodies, handling of tools and materials, and actions in space are related in the thinking processes. Embodied thinking involves information gathering, organising, elaborating, and skilful, real-time adaptation – all in an unfolding process that often happen within a brief span of time. This kind of thinking is visible, for example, in gestures, which are seen as activities of the body that reflect (or are co-produced with) thought. Besides facilitating problem solving and communication, gestures indicate the sensorimotor simulation involved in thinking processes (Hall and Nemirovsky, 2011; see also Alibali and Nathan, 2011; Hostetter and Alibali, 2008).

Method

Participants and the setting of the study

The lamp designing project was a part of larger study that was organised in an elementary school located in a middle-class suburb of Helsinki, Finland. 32 students (13 boys), aged 10-11 years participated in the project; out of these, seven students had linguistic or other educational problems. The lamp designing phase lasted 11 sessions (each session was 45-135 minutes, depending on the class schedule) during a period of two months. The design process was carried through in 13 teams of two to four students, by sketching, drawing, and building prototypes or models. The students also regularly presented their designs to the whole class. The expert, a professional interior designer specialised in lamp and light designing, was present in the classroom; there were extensive, varied interactions between him and the students, including face-to-face discussions with the whole class, to small team conversations, and to the sharing of comments through a networked learning environment, the Knowledge Forum (KF, Scardamalia and Bereiter, 2006).

Data Collection and Methods of Data Analysis

The lamp designing process was video recorded almost entirely, producing about 16 hours of video material from a single camera. During whole-class activities, we recorded the designer's activities, and during small-team activities we followed three student teams. For the present study, we chose a team of three girls, whose design process we were able to follow from the very beginning to the end. They worked on their lamp design from the second to the tenth session, altogether approximately 6,5 hours. The time they used per session varied from 15 to 65 minutes, depending on the class schedule and other activities during the sessions.

For the analysis, we selected the peer collaboration episodes of the team and the episodes where they were interacting with the designer. We adapted Ash's (2007) methodology of three levels – macro, intermediate, and micro – of analysis for tracking meaning making in action. Firstly, in order to form an overall view of the project, we divided all the episodes into five-minute-units (N=76) and defined the main focus of activity in each unit. We identified whether the activity in the units represented 1) ideation, 2) elaborating ideas, 3) defining constraints, 4)

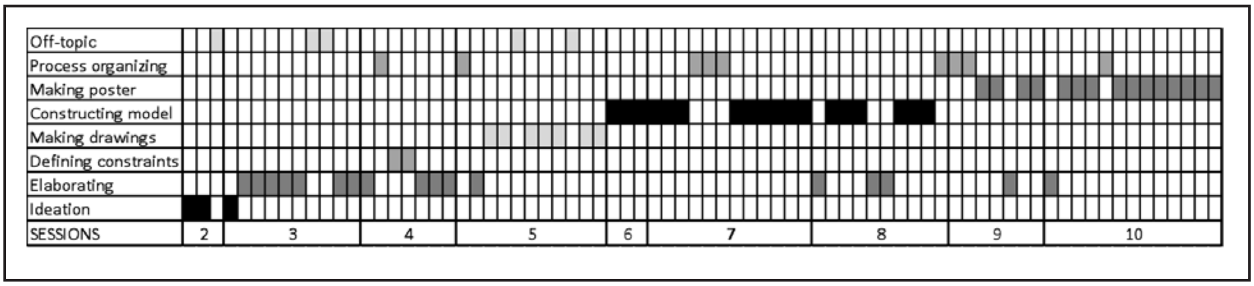

Figure 1. Flow chart of the lamp designing sessions

making drawings, 5) constructing the model, 6) making a poster, 7) process organising, or 8) off-topic activity. Based on this identification, we created a flow chart (Ash, 2007) of the lamp designing sessions, showing the team's major design activities as well as the time they used per session (figure 1). Each square on the flow chart represents one five-minute-unit.

The team started by creating and sketching several design ideas, and developing some of these ideas further. The final idea was chosen during session 3, and elaborated through the subsequent process. The team also made several drawings of their design, from hazy sketches to blueprints on scale 1:1. The most time consuming activity was the construction of the lamp model; the team constructed and put up their lamp from paper, wire, masking tape, and copper pipe during sessions 6, 7, and 8. Making a poster representing their design process and the final product also required a great deal of the team's time.

The second level of analysis was intermediate, i.e., selecting significant events from the flow chart (Ash, 2007). On the basis of identifying the main foci of design activities, as well as our previous analysis on the same data (Kangas, Seitamaa-Hakkarainen and Hakkarainen, 2011a; b), we selected four, on average 15-minute events from the data for deeper analysis. The selected events provided representative slices of time (Ash, 2007) from different phases of the project, exemplifying various kinds of activities (table 1). The first event was from the very beginning of the team's work, and included the first phase of their idea generation. The second event started around the moment where the team's final idea started to take shape. The third event represented designing of measurements, and the last constructing of the lamp model.

The third level of analysis was microgenetic (cf. Ash, 2007). From the selected video recorded events, we analysed each participant' spoken statements (N=1080). After identifying *the speaker*, we classified *the main focus of discourse* of each statement, in order to better understand the content and the proceeding of the team's design process. We identified whether the statement represented 1) visual idea (i.e., shape, pattern, or colour), 2) technical idea (i.e., structure, material, or production method), 3) design constraint, 4) design representation, 5) tool-related talk, 6) process organising (including designer's or teacher's instruction), 7) talk of other team's design, or 8) off-topic talk. In addition, we examined how the participants used *tools, materials, and gestures* to support their verbal communication. Thus, each statement was coded according to its speaker's use of 1) sketching tools, 2) measuring tools, 3) modelling materials or tools, 4) light bulbs, 5) shared view (teacher's computer screen shared through a data projector), 6) pointing gestures (at sketches or other tools), or 7) representational gestures (to describe shape, size, etc.). However, it should be acknowledged that our analysis revealed only the tools and materials used while making verbal statements. Tools and materials were also used without verbal

Session	Design phase	Duration (min:sec)	Statements
2	Generating the first design ideas	13:32	#1–311, N=311
3	Choosing and elaborating the final idea	19:03	#378–706, N=329
4	Designing measurements	14:38	#1336–1626, N=291
8	Constructing the lamp model	11:22	#3982–4130, N=149

Table 1. Significant events selected for the micro-level analysis

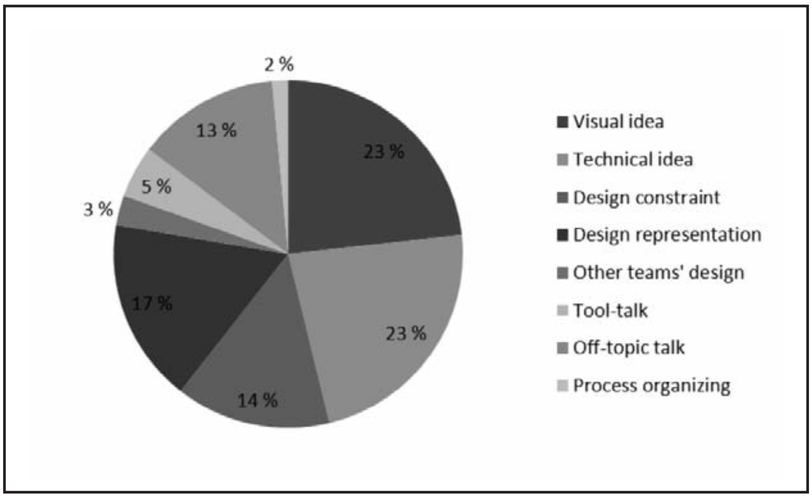

Figure 2. The foci of design discourse during the lamp designing process

communication, but analysing this kind of activity was beyond the scope of the present article. Our aim was to relate discourse to the use of tools, materials, and gestures, thus, the unit of analysis was one statement and tool use without discourse was left out of the analysis.

As noted by Hmelo-Silver and her colleagues (2008; 2009; 2011; Hmelo-Silver, 2003), understanding collaborative thinking and mediation requires going beyond coding individual speech acts. They proposed the use of *Chronologically-Oriented Representations of Discourse and Tool-Related Activity* (CORDTRA) diagrams as one way of understanding about how social interaction and other learning activities serve as tools for students' collaborative thinking. In the present study, we created a CORDTRA diagram for each selected significant event (see table 1). Our diagrams contain a timeline where the speakers, the foci of discourse, and the tools being used are plotted in parallel, enabling their juxtaposition in order to understand the nature of the students' collaborative design thinking (cf. Hmelo-Silver, 2003; Hmelo-Silver et al., 2008; 2009; 2011). Technically the diagrams were created as scatter plots with a commercial spreadsheet software.

Results

The goal of the present paper was to unfold the collaborative design process of one team of elementary students, in order to understand their multimodal ways of design thinking. A team of three girls, Emma, Leila, and Nina[1], designing a pendant lamp was selected for the present study. As an orientation task, the designer asked the students to evaluate the design of lamps in their environment. All of the present participants had evaluated pendant lamps, and therefore, they were asked to form a team for designing a new and better pendant. The design task was rather complex and open-ended in nature, the only fixed requirement was that the lamp's features had to be well grounded in relation to its intended use.

In the following, we will first provide an overview of the team's design thinking. Then, we will unfold the team's process and deepen our analysis on their thinking, as well as consider the role of mediation and embodiment. Because of the limited space, we will present two CORDTRA diagrams, instead of all four. We will present the first and the last diagram, and highlight the different nature of design thinking in these two phases of the process. Diagrams number 2 and 3 did not differ much from diagram number 1, and therefore, we simply provide textual and visual examples of these phases of the process.

Overview of Design Thinking

The major part of the team's utterances during the selected significant events was related to visual or technical aspects of their design, to the design constraints limiting their problem space, or to the design representations (sketches, drawings, model) they produced (figure 2). The team also talked about the tools they used, discussed the designs of other teams in the class, and organised the process. The amount of off-topic talk was relatively high; however, it usually occurred simultaneously with, for example, sketching.

A closer look to the foci of design discourse revealed that various, differing aspects of designing were emphasised in the successive phases of the process (figure 3). Visual ideas were dominant during sessions 2 and 3, whereas technical ideas were the focus of discussion in session 4, and design representations in session 8. The topic of design constraints was present in sessions 2, 3, and 4; the team discussed, for example, issues related to the lamp's use.

The design representations became more and more the centre of discussion towards the end of the project. The more sketches and drawings the team produced, the more such centreing occurred. Furthermore, when the team was constructing their lamp model (session 8), half of their discussion was related to the model. The handling of the physical materials and tools facilitated their considering aspects not pondered previously, as we will describe later.

[1] *All proper names are pseudonyms*

The participants of the team, Emma, Leila, and Nina worked together well, and their design process proceeded rather smoothly. The distribution of statements was quite equal, Leila (*f*=384, 37,2%) and Nina (*f*=367, 35,6%) made almost same number of statements; Emma (*f*=280, 27,2%) a little less. Nina was the most dominant one; she made many initiatives, and many of her statements elaborated her own ideas. Emma was the most silent of the girls; she made fewer initiatives and elaborated them less than the other two. However, many of Emma's statements built on the other girls' ideas, developing them further. Leila also built on others' ideas quite often, and she also made many of the initiatives as well as asked clarifying questions. The team members' different roles were also evident in the distribution of various design tools and materials (figure 4).

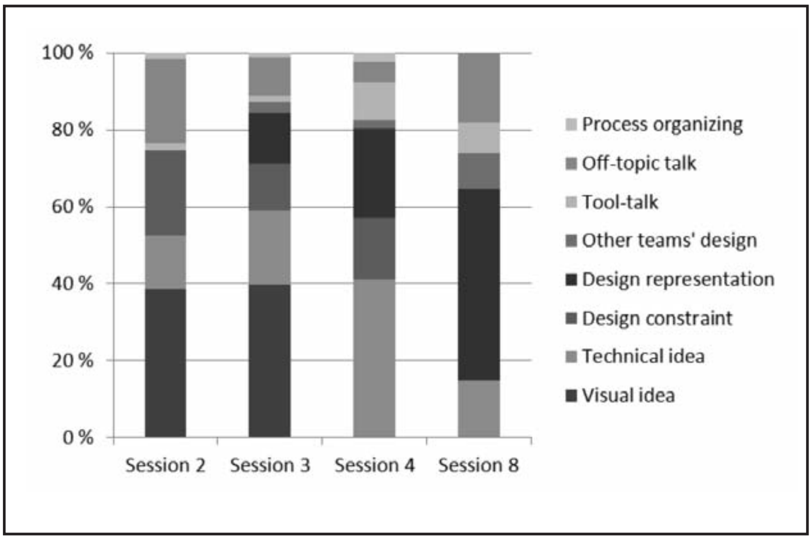

Figure 3. The foci of design discourse during different sessions

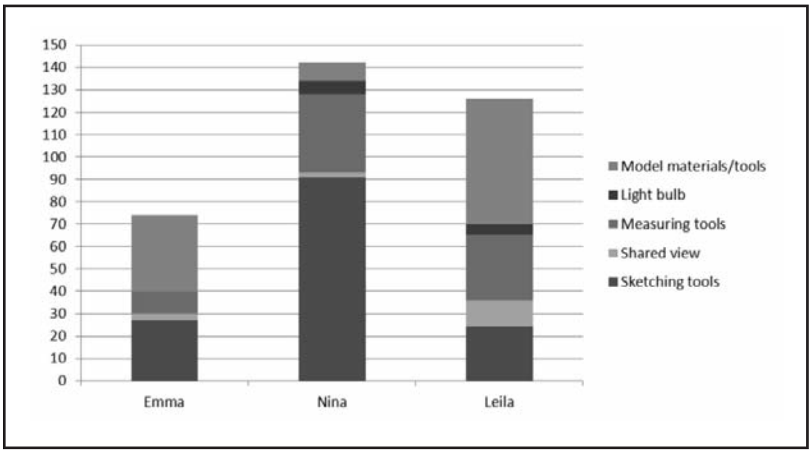

Figure 4. Distribution of design tools and materials between the team members

Nina was using the tools and materials most of all; she especially dominated the handling of sketching tools. Leila used the tools and materials little less than Nina. Notable was her use of the shared view, which she utilised as a support to steer the teams' work into more productive directions. Leila also dominated the use of modelling materials and tools; during session 8 she finished constructing the lamp model, together with Emma. Apart from the modelling materials and tools, Emma used other design tools less than her team members.

Unfolding Design Thinking

As noted by Hmelo-Silver and her colleagues (2008; 2009), the frequencies provide one view of the collaborative design process, but do not afford a sense of chronology nor information on particular qualitative features of the discourse. In order to examine how the different aspects of discourse relate to each other, and to the use of tools, materials and gestures, we created four CORDTRA diagrams for several phases of the team's work (see table 1). In the following, we will present two of these diagrams (figures 6 and 11). At the bottom of the diagrams, there is a running count of the statements. The vertical axis shows all the categories: participants (at the bottom), the foci of design discourse (in the middle), and tools (at the top). The patterns of collaborative, multimodal design thinking, i.e., the speaker, the focus of discourse, and tools of each statement, are arranged on the horizontal axis in chronological order.

Generating the first design ideas

Our first significant event and the related CORDTRA diagram (figure 6) is from the very beginning of the team's collaborative work, when they started to generate ideas for a new pendant. During this event they produced 11 different design ideas (figure 5), considering both visual and technical aspects, as well as constraints related to their ideas. Naturally, generating visual ideas was the central activity in this phase, especially in the beginning. The team used representative gestures, and later also

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pointing gestures, sketching tools, and the shared view to support their idea generation and communication.

At first, the team's designing was mostly horizontal (Seitamaa-Hakkarainen and Hakkarainen, 2004; see also Goel, 1995): They created one visual idea after another, without elaborating any of them much further. These ideas were described verbally and with representational gestures. Idea number seven, "The Lamp with Hundred Strings" (statements #44-114) was the first vertically developed idea, which indicated that the idea was provisionally accepted and elaborated (see Al-Doy and Evans, 2011). This idea was initiated by Nina, and she also spontaneously started using sketching (#51) to support her verbal explanation. It appears that sketching facilitated the teams' developing their idea further and to a more detailed level. Compared to the previous six design ideas altogether, this sequence contained almost a double amount of statements. No off-topic talk occurred during this sequence. Nina elaborated her idea verbally and visually, and both Leila and Emma built on her ideas. In addition, Leila asked Nina to clarify several features of the design. Besides considering the shape and colour of the lamp, the team also discussed technical aspects of their design, such as structure and functionality. Due to the difficulties in elaborating the technical elements, the team finally gave up the design idea.

After "The Lamp with Hundred Strings" sequence, the team used sketching throughout the episode. From statement #135 onwards, and after the teacher had reminded the class, they also used the shared view to support their designing. On the screen was the designer's

Figure 5. The team's initial design ideas

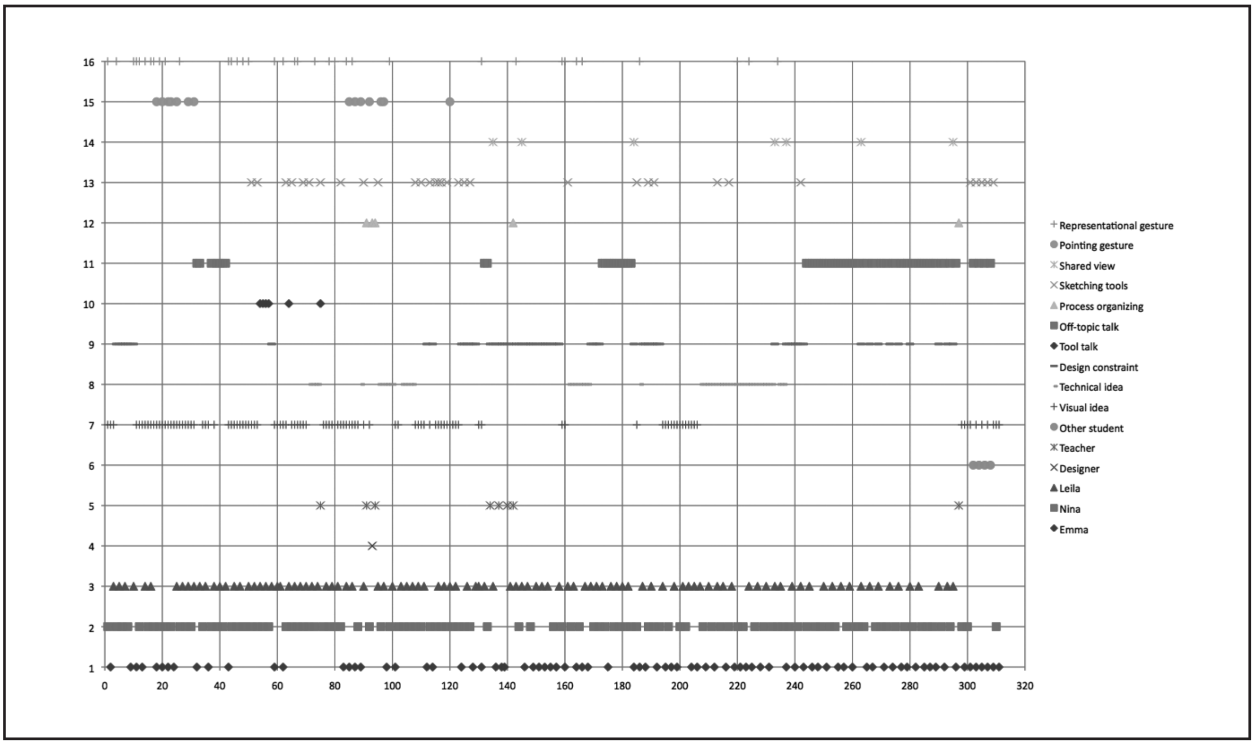

Figure 6. Generating the first design ideas (Session 2)

note from the KF "Lamp Designing" view. He had listed constraints to be considered while generating the design ideas, for example, the purpose of the lamp and users' needs. "The Disco Lamp" (idea number 10, statements #159-243) was the second vertically developed idea of the team; it was also the first design idea in which the team considered both visual and technical aspects, as well as the constraints related to their idea. They considered where the lamp could be used, who would use it, and how well it would light up the area. This idea was also jointly rejected, because the team agreed that there is no real need for their disco lamp.

Choosing and elaborating the final idea

After session 2, the team continued generating more design ideas; altogether they produced 17 different ideas for a pendant lamp. Our second significant event began from statement #378 (session 3), around which the team's final idea started to take shape. Nina presented an idea of a hanging pendant lamp where the light would come from both the bottom and above of the shade. Although the idea was still very sketchy (Figure 7) Leila immediately showed her interest by asking clarifying questions and building on the idea:

Extract 1. The idea of a pendant lamp

378 Nina *(showing her sketch)*: Haha, this kind, … this way around, like from Leila's direction, this is hanging from the ceiling.
379 Leila: Oh, so is it [my orientation of the sketch] the wrong way around?
380 Nina: Yeah so this [lamp] is hanging from the ceiling.
381 Leila: So how does the light …, come from there?
382 Nina: It reflects off that [shade].
383 Leila: So where is the lamp again?
384 Nina: Inside there. You could make a hole here [top of the shade], and then it comes from here.
385 Emma: Maybe not.
386 Nina: Yeah.
387 Leila *(sketching)*: Ha-ha, hey I know, wait, we're doing now, doing these chain things, like this.
388 Nina: A hole like that.
389 Leila: Look, now, this kind [has a hole] that's on both sides, because it [light] comes from up there.

Nina was not so interested in her own idea, and she moved on to the next, but Leila continued developing and sketching the idea of the hanging pendant. She was eager to reach the decision about the final idea and kept pushing Nina and Emma to make the decision with her by asking repeatedly where and what the lamp would be used for. Finally Leila's attempts succeeded and the team made a decision that the lamp would be used over a dining table, in a kitchen or dining room. While discussing these topics, Nina was still sketching new ideas:

Extract 2. Reaching a decision

437 Leila: Yeah, yeah, so, let's make it, um, what's the lamp, what's it needed for? For the living room or kitchen or where?
438 Emma: It could fit into the kitchen, but it doesn't really, because it doesn't produce much light and anyway you need quite a lot in the kitchen.
439 Leila: The dining room.
440 Emma: Dining room?
441 Leila: Yeah, above the table.
442 Emma: Maybe.
443 Nina (sketching): Well that's what I meant.
444 Leila: Oh but you said, you said the kitchen.
445 Emma: So that there's a table there, that's how it hangs off there.
446 Nina: Look I invented a new lamp.
447 Leila: Well try to decide which one we are using.
448 Nina: No, but I invented a new lamp.
449 Emma: Why couldn't this one also have squares [decorating the shade]?
450 Leila: Yeah I'm just drawing it.
451 Nina: It doesn't fit. Leila look, I made a good one, Leila.
452 Leila: Wait, what do you mean squares don't fit this one?
453 Nina: You don't know how to do it, it's like this, oho, me neither. This doesn't fit here at all.
454 Leila: Yes it does.
455 Nina: Look, isn't it beautiful?
456 Leila: Yeah! That's how it could be.

Through Nina's sketching, Leila's clarifying questions and repeated requests to consider the needs for the lamp, and Emma's idea to include squares on the shade (an idea

Figure 7. The idea of a pendant lamp

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presented previously), the team gradually approached their final idea (figure 8). Besides the decision of the lamp's use, the team made joint decisions concerning the visual aspects of their idea, which was the central activity also during this event. They, for example, considered the shape and size of different parts of the lamp, as well as the pattern and colouring alternatives of the shade. On Leila's initiative, the team used the designer's questions on the shared view to support, also, technical aspects of their designing, such as the options to dim and rotate the lamp.

Before reaching the decision of the final idea, the girls were each generating several ideas, some of them simultaneously, and sharing them only partially. After reaching the decision on the final idea, the team's activities matured towards more successful collaboration. Their attention was jointly focused, the object of activity was mutually shared, and they were also organising their activities collaboratively (Barron, 2000).

Designing measurements

The third significant event was from session 4, when the team was determining the measurements of their pendant lamp. During this event, the technical aspects of designing were in the focus of discussion; the team carefully considered the dimensions of parts of their lamp. In addition, they thought about the constraints related to the measurements, such as the proper length of the lamp in relation to the height of humans who might be walking beneath the lamp.

The role of embodied thinking, i.e., handling of tools and use of space, became more evident during this event. In the beginning, the designer showed the girls how they can hold a measuring tape towards the ceiling to help them in visualising the lamp's size (figure 9, left). This prompted the team to begin consideration of how high up the lamp should be so that nobody's head would bump into it. They went back to their drawing desk, and used also a light bulb for designing and sketching the measurements of their lamp (figure 9, middle). Shortly after this, they climbed over another desk, in order to envision the dimensions more accurately. One of the students held a telescopic pointer, the second a sketch of the shade, and the third one was assessing the whole from a distance (figure 9, right). Throughout the event, the team moved back and forth between the two desks, measuring and drawing, and gradually adjusting the measurements until satisfactory and mutual decisions were reached.

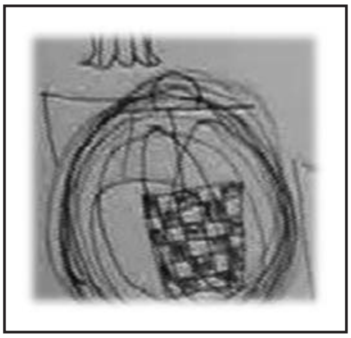

Figure 8. The final idea

The sub-task of determining the measurements was difficult for the team to concretise; therefore, externalisation and objectification were needed. Real-time adaptation of the dimensions of body and space, as well as handling of the tools, facilitated the team's efforts to consider and re-consider the measurements several times, taking into account the relevant constraints. Moreover, the task would have been difficult, even impossible to complete single-handed. It required participation and joint reflection, hence supporting successful collaboration and learning (cf. Sawyer, 2012).

Constructing the lamp model

The last significant event and the related CORDTRA diagram (figure 11), from session 8, differ from the previous events in two ways. First, the number of statements is significantly lower (149 compared to 310, which is the mean number of statements of the other events, see table 1). The team was constantly handling tools and materials, but making utterances mostly at long intervals. Second, almost half of the statements (49,7%) were focused on the design representation, i.e., the lamp model, as such (see figure 3). The girls talked about things such as how they should hold the parts, how much tape they should use, and so on. The small number of statements, as well as their concentration on the model, indicated that it was a demanding task to construct the lamp, and that the team was fully engaged in this activity. According to Patel (2008) this kind of focused engagement is a definite indicator of embodied thinking, and the process of embodied learning is marked by real-time adaptations.

Before the event, the girls had finished the shade of their lamp and the cover plate for the cord and connectors (both made of paper), and were now considering how to attach these to the supporting bar (copper pipe). This was an issue that the designer had previously asked them to think about, but which was difficult for them to imagine and draw. Thus, they never really pondered on the issue, until when they started to handle the concrete materials, the three-dimensional lamp parts (figure 10). The parts functioned as material scaffolds; the students did not just have to *imagine* how the shade of the lamp and the supporting bar inside it would look because with the model they could actually see them and physically turn them into different positions. They, in fact, made the decisions regarding the attachment rather quickly, in less than three minutes (statements up to #4050); the rest of the event was used for fixing the shade and the bar together with wire and masking tape. Their capacity to find a quick, matching response to the existing situation, and to improvise with available materials indicates to the ability to think and learn "on the job" (Patel, 2008).

Discussion

In the present study, design learning was regarded as a mode of constructing knowledge through action and making; a process driven by exploration and experimentation, making and constructing, and reflection. When analysing design learning, it is important to evaluate the process and construction of the designs. Designing challenges students to think in new ways and take risks. The open-ended and complex design tasks require focusing on harnessing that engagement, and supporting students as they propose ideas, fail, and propose again. The management of the whole design process forms the basis of critical understanding of the practice. Further, designing and learning by designing are also social processes, where collaboration is needed. The multifaceted nature of designing encourages shared meaning-making through identifying and negotiating various alternatives, constraints, and possible solutions. The present study aimed to build upon previous studies on design learning by documenting, in detail, elementary students' design thinking during a project where the foregoing viewpoints were deliberately fostered. In the following, we discuss how these aspects were realised in the students' activities.

The design task of the lamp designing project was a rather complex and open-ended real-world problem; it was based on the findings that the students made in their studies of existing lamps. Completing the task required mastering specific knowledge and skills, which accumulated while the students were engaged in repeated cycles of designing, throughout the project. Design problems are complex wholes, and cannot be parcelled out to individual skills; the required knowledge and skills are learned more efficiently, if the students learn them while solving authentic problems (Lahti, Seitamaa-Hakkarainen, and Hakkarainen, 2004; Sawyer, 2012). Furthermore, the design problem space is determined and limited through a set of constraints. During the lamp designing project, the students were able to take into account many constraints related to lamp designing, such as user needs, because these were emphasised by the professional designer. This helped the students to concentrate on features beyond the aspects on which novice designers tend to focus (e.g., appearance). Our results are in line with Sawyer's (2012) findings, which indicate that constraints help the students to focus on relevant aspects of the problem at hand, as well as to move beyond their familiar patterns and existing misconceptions. Many learning scientists agree that the most effective learning environments are highly constrained, while still allowing the students to engage in authentic, situated inquiry practices (Sawyer, 2012).

The fundamental role of design representations (sketches, drawings, models) for design thinking and communication is widely acknowledged in research on design education; also our findings underscore their importance. Producing external representations of design thinking facilitated the students in both horizontal and vertical ideation. They produced several design ideas, and also elaborated many of them further, considering both visual and technical features of the ideas, which is not typical for elementary aged students (Hope, 2005). Besides using the design representations for illustrative and communicative purposes, the students used them as design tools for developing their ideas. Our findings also emphasise the embodied dimension of design learning; they show how engaging in embodied activities can facilitate the students' moving into innovative, real-time design thinking processes that are otherwise beyond their capabilities. Competence in designing cannot be reached through interaction that is merely verbal; rather it is dependent on

Figure 9. Employing tools and dimensions of body and space for designing measurements of the lamp

Figure 10. Constructing the lamp model

materially mediated and embodied communication, interaction with fellow participants using physical artefacts and space (Johansson and Illum, 2009).

The collaborative lamp designing process was affected by the participants' willingness to listen and share each other's ideas, even though their participation was not completely equal. Since the process was spread over a two-month period, the students had the possibility to create several ideas, and to negotiate until they found functional and mutually acceptable solutions. During conversation, they were attending to each others' understandings of the issues, while simultaneously settling social relationships (see also Rowell, 2002). The emergence of a shared design idea – which did occur – was essential for successful, collaborative design learning process.

In the present study, we used the CORDTRA technique to study face-to-face collaboration in design learning context at elementary level. To avoid excessive difficulty in interpretation of the diagrams, we carefully selected four events from the extensive video data. The selection was a kind of "pre-zooming" in the data, allowing us to explore interesting phenomenon more deeply in varying phases of the process. According to Hmelo-Silver and her colleagues (2009; 2011) a CORDTRA diagram should always be interpreted together with the corresponding discourse, zooming in on interesting patterns on the diagram and going back and forth between the diagram and the coded discourse. In the present study, it was also necessary to go back to the video data to examine the non-verbal activities, such as gestures and tool use, in order to understand the multimodality of the students' design thinking. However, the CORDTRA diagrams provided a means to analyse the longitudinal, complex and iterative design process in a structured and detailed manner, thus enabling us to capture both the details and the overall context of the process.

In general, the purpose of design learning is to provide a framework for teaching students to become actively involved in shaping their environment. The findings of the present study indicate that in order for learning by designing to be effective, it is best founded on projects based on real-world problems, projects eliciting processes that resemble the multimodal ways of thinking and acting that professional designers engage in their everyday working life. Taking part in the collaborative design process provided opportunities for learning the foundational design skills by engaging the students in carrying out various concrete and material, as well as epistemic and conceptual activities. In the course of these activities (i.e., drawing, writing, measuring, and model making) they learned to conceptualise, reflect, and communicate their design ideas. Sawyer (2012) argues that the cultural model of teaching and learning designing (i.e., studio model) has implications beyond art and design education. It may help learning scientists to resolve longstanding tensions faced in, for example, educational reforms in STEM disciplines. Our results support these arguments; the multifaceted design tasks integrate skills which are also needed in science, technology, engineering and mathematics.

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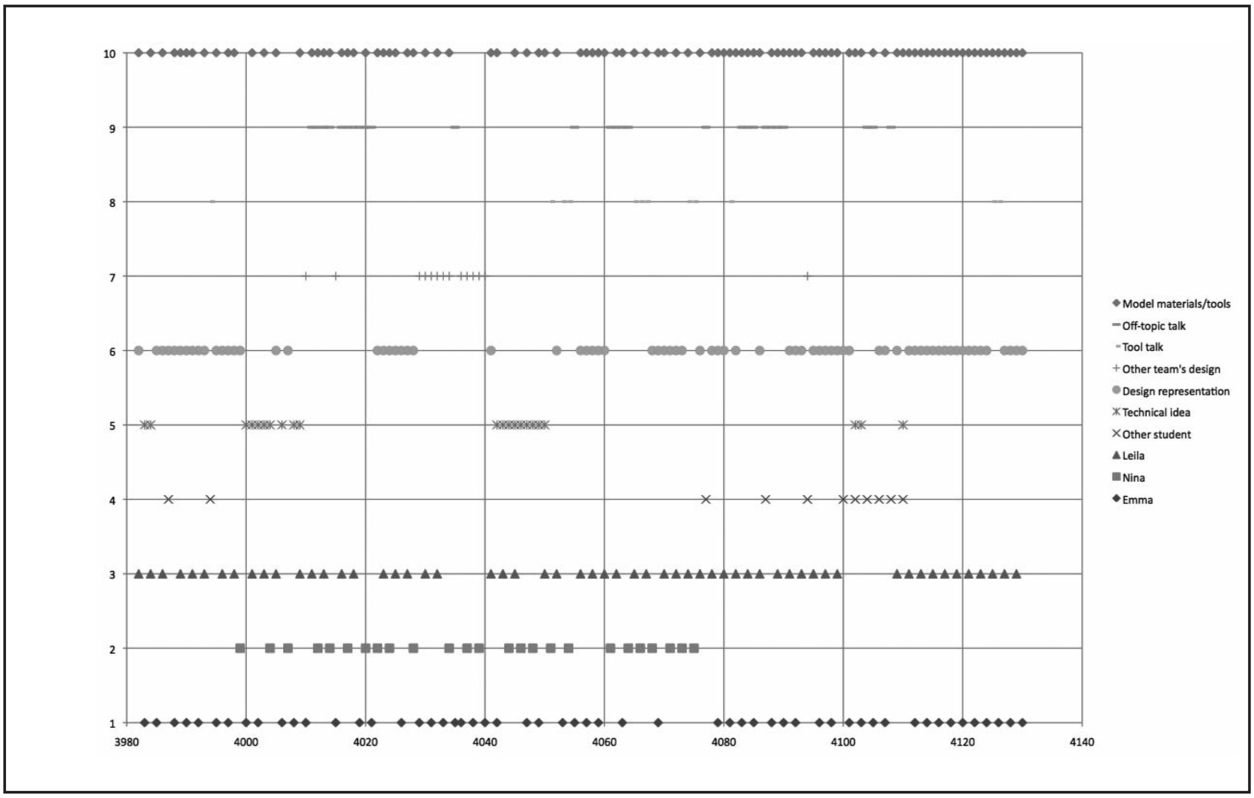

Figure 11. Constructing the lamp model (Session 8)

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kaiju.kangas@helsinki.fi
pirita.seitamaa-hakkarainen@helsinki.fi
kai.hakkarainen@utu.fi