To cite this article: Härkki, T., Seitamaa-Hakkarainen, P., & Hakkarainen, K. (2018). Line by line, part by part – collaborative sketching for designing. ***International Journal of Technology and Design Education, 28*****(2), 471-494.**

The final publication is available at linki.springer.com
https://link.springer.com/article/10.1007/s10798-016-9379-7

Line by line, part by part–collaborative sketching for designing

Abstract

While sketching has an established role in professional design, its benefits and role in design education are subjects that invite research and opinions. We investigated how undergraduates studying to become design educators and textile teachers used sketching to generate and develop design solutions in a collaborative setting. The students were given an authentic design assignment involving three detailed tasks, one of which was 2D visualisation by sketching. Adopting a micro-analytical approach, we analysed the video-recorded visualisation session to understand how teams used sketching to collaborate and to generate and develop design solutions. To that end, we set three research questions: (1) What ways of collaborative working are reflected in actions of sketching? (2) In what ways do sequences of collaborative sketching contribute to designing? (3) What kinds of collaborative sequences of sketching advance designing? Our analysis identified three collaborative ways of sketching (co-ordinated, collective and disclosed) and confirmed that sketching is an important facilitator of mutual appropriation, adaption and adoption. Next, we identified three ways of contributing to designing, as well as three functions and six capacities for advancing designing. Our analysis shows that sketching can lead to invaluable advances in designing, although each team had its own way of using and benefiting from sketching. We further consider that the teams' diverse sketching processes and rich content owed, at least in part, to the task structure and imposed constraints. We continue to see sketching as an important design tool, one among many.

Keywords: collaborative design – higher education – sketching – video analysis

Introduction

In higher education, not all students are studying design to become professional designers; undergraduate textile teacher students at a Finnish university are studying to become teachers who teach designing and crafts to pupils and adults. Therefore, the curriculum should provide them with a good command of design tools and processes, even though design is not their main subject. Our previous study indicated that textile teacher students had an ambivalent relationship with the design process and with the use of sketching as a medium for expressing design concepts and developing design ideas (Authors 2014a). While in that study students designed individually, the present study focuses on student teams' sketching processes, and especially on *how sketching is used to generate and further develop design solutions in collaboration*. By collaboration, we refer to having joint goals and actively working together to produce a single outcome (Hennessy and Murphy 1999), as well as to mutual appropriation, being receptive to adoption and adaption and making knowledge and practices visible (John-Steiner 2000).

While developing pedagogies and educational approaches for teaching designing, research on students' design processes is necessary, as is understanding the practices of professional designers. In professional design, research on sketching is piling up, and the importance of sketching for thinking has long been celebrated (for a review, see Purcell and Gero 1998; van der Lugt 2005). However, research results on design education are not straightforward. Studies of novice designers under the age of 16 show that younger children tend to prefer three-dimensional modelling to sketching when generating, developing and communicating design proposals (Hope 2005; Rowell 2002; Schwarz et al. 2009; Welch 1998). Moreover, children tend to use sketching for representational rather than generative purposes (Schwarz et al. 2009), possibly because of that emphasis in school art classes (MacDonald et al. 2007). However, studies of novice designers at undergraduate level show that students benefit from sketching because it serves as a thinking tool and a repository for ideas (Römer et al. 2000), and that sketching supports every aspect of students' design process (Cardella et al. 2006). Yang (2008) recognised a clear relationship between the volume of dimensioned drawings generated and the quality of the design outcome; in an earlier study (Yang and Cham 2007), however, no relationship was found between sketching skills and design outcomes. It seems, then, that *students at higher educational levels sketch and benefit from sketching more than students at lower educational levels*. Because sketching (or drawing) is a highly complicated behaviour consisting of multiple cognitive components, including visual analysis, visuomotor transformation, planning and execution of the complex sequential motor plan (Trojano et al. 2008), it is reasonable to suppose that experience has implications for the use of sketching. Jonson (2005) raised an important point, which is that *the implications of the design environment need to be considered when interpreting results*. In his study, verbalisation was identified as the primary conceptual tool, even though all the participating students reported that they would have liked to do more sketching (Jonson 2005). All in all, sketching is an acknowledged thinking tool for designing (Cross 1982; Goel 1995; Lawson 1997; Schön 1983; Authors 2001) that has its place in design education. According to an international survey on university-level basic design education across 22 countries, a quarter of those educational programs included visualisation by freehand sketching in their curriculum (Boucharenc 2006).

Research on professional design has shown somewhat similar results regarding the role of experience. Novices prefer 3D visualisations to 2D visualisations (Ahmed et al. 2013), and experts benefit more than novices from sketching during idea generation (Goldschmidt 1991; Suwa and Tversky 1997). However, Eisentraut and Günther (1997) note that while drawing by hand is important to designers, the use of visualisations depends on the designer's style of problem solving. Furthermore, while Bilda, Gero and Purcell (2006) suggest that expert designers may not need to sketch during conceptual designing, they also speculate that it may be that long experience of progressing their ideas through sketching that enables them to design through mental imagery only, without sketching. In addition, they emphasise the importance of sketching for learning how to design.

Professional designers sketch for a reason—the most obvious being to show how a design will look and function (Ferguson 1992) without the need to construct the actual object. However, our interest lies in how sketching supports the exploration—the generation, evaluation, refinement and reinterpretation of ideas. *First, sketching provides an extension to memory* (Goel 1995), which enables the designer to manage more complex situations than would be possible with mental imagery alone (cf. distributed cognition by Hutchins 1995; Zhang and Norman 1994). The commonly recognised functions of sketching include storing, archiving (Ullman et al. 1990; Tang 1991) and communication of ideas (Bucciarelli 1996; Perry and Sanderson 1998; Ullman et al. 1990), as well as mediating interaction (Tang 1991). *Second, sketching supports iterative efforts to produce ideas*. Goldschmidt (1991) argues that designers who are engaged in sketching do not externalise images held in the mind but create a particular image while sketching it. The marks created on paper stimulate the imagination, which, in turn, may influence the sketch in process (Fish and Scrivener 1990) or help to induce all-new images (Goldschmidt 1991; Schön and Wiggins 1992). Yet the invaluable aspect of a sketch is not what it contains but what it implies, and the multiple interpretations it allows (Goel and Pirolli 1992; Suwa and Tversky 1997), whether intended or unintended. *Third, sketching provides a tool to evaluate and test ideas.* Sketching substantiates an idea, making it easier to evaluate. Schön (1983) was the first to introduce design as the construction of knowledge. For him, moving—making changes to a sketch or design—plays a fundamental twofold role: (1) testing whether the idea is applicable and in logical conformity with earlier moves and (2) probing and shaping the problem. Sketching brings into the process previously unused design knowledge (Schön and Wiggings 1992), such as ideas, features, functions and constraints.

The explorative cycles of sketching, reinterpretation and evaluation are central to the production of design ideas (Menezes and Lawson 2006). Design research on these cycles has produced many conceptualisations, such as ‘seeing as’ and ’seeing that’ (Goldschmidt 1991), ‘seeing-moving-seeing’ (Schön 1983), ‘imaging’, ‘presenting’, ‘testing’ (Zeisel 1981), ‘naming’, ‘framing’, moving’, ‘reflecting’ (Valkenburg and Dorst 1998), as well as categorisation schemes (Kavakli and Gero 2001). In these analyses, the contributions of sketching and speech were treated as equal. However, in van der Lugt’s (2005) study of whether sketches invite the production of new sketches, participants reinterpreted their own sketches to produce ‘sketches built on sketches’. Contrary to the initial hypothesis, other participants’ sketches did not invite them to make reinterpretations (van der Lugt 2005). This behaviour, if consistent throughout collaborative design, would considerably diminish the benefits of teamwork, such as adapting and adopting, sharing and building on each other’s ideas—a disquieting thought for design educators.

Design education should equip students with essential skills and tools. Our previous study showed that during a design and make assignment, junior high school students produced only simple line-work, and only a few of them provided more developmental sketching with variations of shape and detail (Authors 2014b). Students’ sketching skills, however, are the product of the activities they participate in, either at school or during their leisure time. While the use of sketching as a thinking tool may not be mainstream in Finnish schools, it is all the more important to include that function in teacher education, and to properly investigate students’ sketching processes.

To examine how collaboration is reflected in sketching and how epistemically meaningful collaborative sketching actions interact and are linked to advance designing, that is, to promote the accomplishment of a collective design solution, we posed three questions about collaborative sketching:

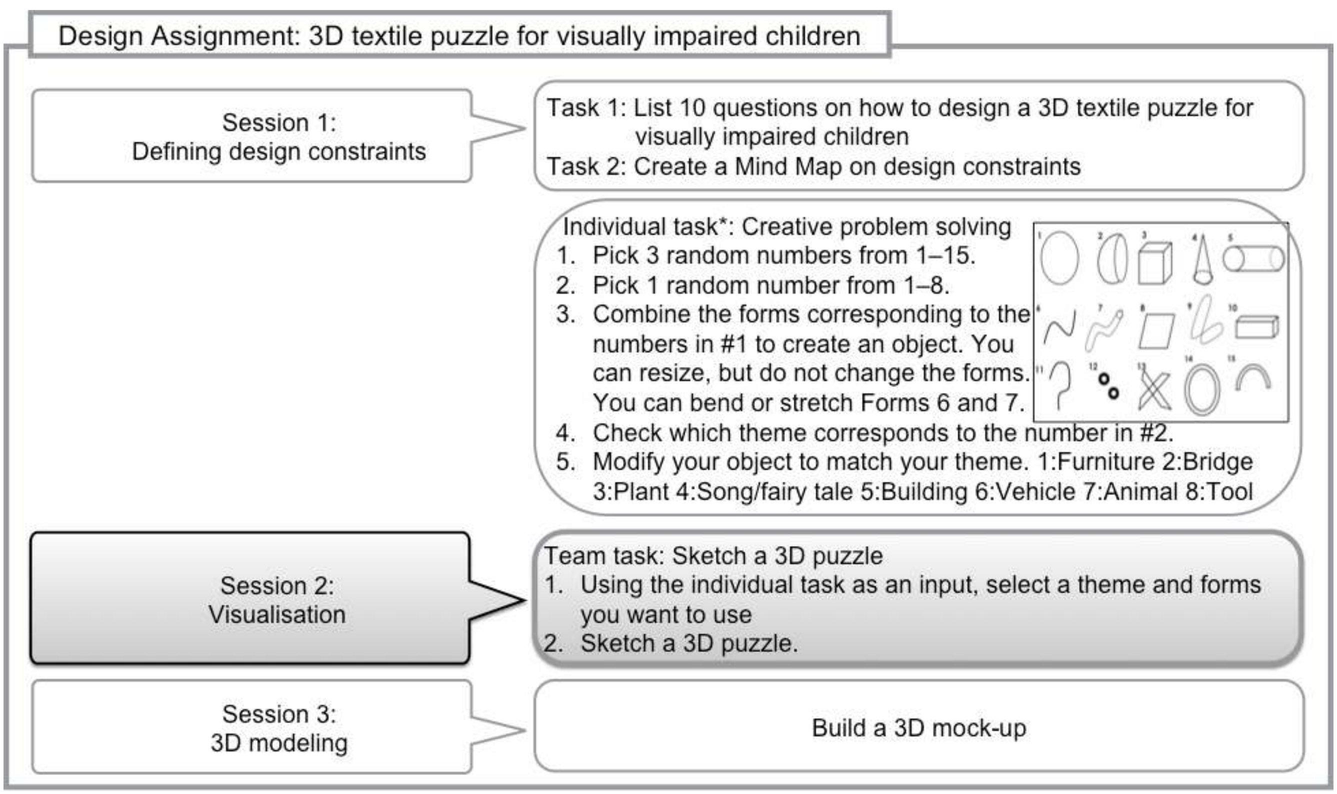
1) What ways of collaborative working are reflected in actions of sketching?
2) In what ways do sequences of collaborative sketching contribute to designing?
3) What kinds of collaborative sequences of sketching advance designing?

The questions correspond to three layers of analysis from (1) sketching events to (2) sketching events within collaborative sequences and (3) collaborative sketching sequences. In the following sections, we will first provide an overview of our research setting and the three-layer analytical method we have developed, then present the results and conclude with a discussion.

Methods

Setting: designing a 3D textile puzzle for visually impaired children

The present study, forming part of the XX research project, focused on collaborative sketching processes and utilised data collected in an innovative higher education setting. In the setting, teams of first-year undergraduate textile teacher students at the University of Helsinki undertook an authentic design assignment, *a 3D textile puzzle for visually impaired children aged 3–6*. These children, real-world clients, were represented by Celia, a library for all print-disabled people. The client perspective—the needs of visually impaired children—was presented to students in the form of the Celia guidebook for making tactile books, a 20-page booklet available (in Finnish) at the Celia website (www.celia.fi).



Note: *As an input to the visualisation team task, students individually completed one classical creative problem-solving task (adapted from Sawyer 2013).

Fig. 1 Design assignment *functional 3D puzzle for visually impaired children*; the scope of this study appears in grey

The design assignment imposed constraints on student teams, such as a time-pressured schedule and a low budget, and offered a supporting structure entailing three detailed tasks to focus their attention on aspects of a professional designer's work: identifying design premises and formgiving in 2D and 3D modelling (Fig. 1). At the same time, the task structure provided future teachers with a practical introduction to common design tools, such as sketching and 3D modelling, and an example of a pedagogical structure for collaborative design. The pedagogical structure was progressive in nature, as not all the information was given to teams at the outset; this gradual introduction of new instructions, tools and materials was intended to inspire the teams to further develop their designs. Our overall aim was to encourage novice students to innovate, play, explore and stretch the limits of their creativity within a longer collaborative assignment.

The setting formed part of a compulsory course called *The Basics of Craft Science and Design*. Due to student schedules, all data collection occurred during classes, which put serious stress on the availability of both facilities and cameramen and dictated the number of teams we could select for the study. Ultimately, 12 students aged between 20 and 48 years were selected from the 36 course participants. Selection was based on their willingness and ability to participate in the sewing technology course in which the designs were completed; we believed that the opportunity to make the puzzle might increase student motivation and commitment, as well as pose a limiting constraint in terms of the teams' sewing skills. The students were assigned to teams of three, based on their curriculum and on their answers to questions about their sketching habits asked at the beginning of the course. None of the students sketched on a daily basis, but one or two students in each team felt that sketching was a natural way to express ideas.

We video-recorded all three sessions of the four teams with one top-view camera and one side-view camera, and we collected all the documents the teams produced. Following the design phase, we also video-recorded stimulated recall team interviews. Because the present study focused on sketching, only those data relevant for the visualisation session were included in the analysis. Given that restriction, the data corpus for the study was comprised of 2x3 hours of video for design sessions, 4.5 hours for team interviews and 26 working documents.

We named the teams after the designs they produced: Team Truck, Team Landscape, Team Robot and Team Ball. Preliminary viewing of the video footage revealed that one of the teams, Team Ball, preferred to develop their key solution verbally rather than by sketching. They decided to create a nonrepresentational structure composed of geometric forms. Soon, they picked a 3D structure from a sewing pattern book, and focused on ideating—verbally—innovative fastenings, as well as haptic, visual and scent-based features. In the end interview, the team reported that they considered neither a sketch nor a 3D mock-up adequate; instead, they expressed a need for a textile pilot to fully comprehend their complicated 3D structure. Taking all this together, we concluded that sketching did not play a meaningful role in their design process and excluded Team Ball from the detailed analysis. Despite this decision, we do not wish to devalue their otherwise creative design process. The scope of the present study and the overall flow of the design assignment appear in Table 1.

Table 1 Overall view of the design assignment (Authors 2016a); the scope of this study appears in grey

	Team Truck	**Team Robot**	**Team Landscape**	**Team Ball**
		Session 1: Defining design constraints		
Duration	53 minutes	64 minutes	42 minutes	36 minutes
Outcome	No formulated solution or structural ideas	2 preliminary ideas: doll, animal	1 committed solution idea: landscape	2 competing ideas: ball and pyramid
		Session 2: Visualisation		
Duration	49 minutes	1 hour 18 minutes	47 minutes	1 hour 8 minutes
Outcome of individual task*	3 themes: building, animal, vehicle 7 forms	1 theme: song/fairy-tale 7 forms	3 themes: plant, animal, song/fairy-tale 7 forms	2 themes: animal, building 8 forms
Teamwork outcome	Line drawing with a list of possible fastenings	Line drawing with structural and functional details	3 inscriptions with structural, functional and measurement details	Line drawing with structural and functional details
		Session 3: 3D modelling		
Duration	1 hour 29 minutes	1 hour 21 minutes	1 hour 8 minutes	1 hour 21 minutes
Outcome	Paper mock-up with one added feature	Wire and fibre-fabric mock-up of finalised quality	Clay mock-up with highly detailed surface, solutions for implementation	Wire mock-up, solutions for implementation
Outcome of the design assignment				

Note: *As an input to teamwork, each team member selected one random theme and three forms. In some cases, different team members selected the same themes and forms, resulting in fewer options for teamwork.

Three-layer analysis method

To capture emergent collaborative processes, systematic and rigorous methods are needed. Our previous study (Authors 2016a), also part of the XX research project, utilised a method based on segmentation at two-minute intervals. That approach permitted macro-level analysis of design activities. However, capturing interesting process-level variants of the collaborative sketching the teams engaged in, and the different roles those variants played in finding a collective design solution, required a more fine-grained method. For that reason, a new method was developed to address the epistemically meaningful actions of sketching. Additionally, following Roth and McGinn (1988), our analysis utilised the analytical concept of *inscribing* to refer to sketching as well as writing.

To examine sketching processes from two viewpoints—how they reflect collaboration and how they contribute to the advancement of designing—we examined three layers of collaborative sketching: (1) micro-level actions of inscribing—that is, inscribing-events; (2) collaborative inscribing-events and linked neighbouring speech—that is, inscribing-sequences that are epistemically meaningful for collaborative designing; and (3) the kinds of collaborative, epistemically meaningful inscribing-sequences that advance designing. Consequently, our analysis method entails three hierarchical layers, in which the lower layers filter and feed findings to the higher layers (Table 2).

Table 2 Three-layer analysis method as a filtering device

Layer	Unit of analysis	Criteria to categorise and filter	Outcomes of analysis
Event	Event: an individual team member inscribes	Ways of collaborative working reflected by inscribing	Categorised collaborative inscribing-events
Sequence	Sequence: collaborative inscribing-events of more than one team member linked with collaborative turns-at-talk; contributions add significant value	Purpose of within-sequence inscribing-event(s)	Categorised inscribing-sequences that contribute to designing
Advancement	Sequence that advances designing	Function and capacity of the inscribing-sequence	Qualitatively described capacities of collaborative inscribing to advance designing

In the analysis, we used the video analysis software INTERACT. A detailed description of the method appears in the following paragraphs.

From pen strokes to events and ways of collaborative working

At this layer of analysis, we focused on individual team members. The elemental operation of inscribing is the pen stroke, which creates visible marks-on-paper; a pen touches a sheet and begins moving until the pen is lifted from the paper. In our data, one pen stroke could last as little as 0.1 second. To see the forest for the trees, we defined our inscribing-event according to Garner's (2001) Graphic Act as 'continuous sketching or writing activity where pauses, interruptions, etc. are less than one second in duration.' On that basis, the average event time was nine seconds.

We first categorised inscribing-events as sketching and writing. The second categorisation was based on team members' explicated intentions, which characterised the teams' ways of collaborative working. To identify intentions, we scrutinised turns-at-talk and other actions in close proximity to the inscribing-event. Finally, we identified four data-driven categories: co-ordinated, disclosed, collective and private inscribing-events (Table 3).

Table 3 Categorisation for inscribing-events

Categories	Intention: a team member inscribes because…
Co-ordinated	… the team agreed on a division of labour, and that everyone should concurrently inscribe their own proposal.
Disclosed	… he or she wants to share an illustrated idea with the other team members. An inscribing-event precedes verbal disclosure.
Collective	… the team has accepted a feature, which he or she adds to the team's collective solution.
Private	*No expressed intention*: he or she inscribes but does not share—verbally or otherwise—the result with other team members.

Co-ordinated, disclosed and collective inscribing characterise different ways of collaborating. The differences lie in how the team regulates the division of labour, whether explicitly negotiating prior to acting (co-ordinated, collective) or based on the spontaneous flow of the design conversation (disclosed, private). Private inscribing-events had no shared meaning. In general, private events might be productive from the viewpoint of the scribe (see, for instance, Schott 2011), but from the collaborative viewpoint, they have no obvious meaning. For this reason, private events were excluded from further analysis.

From events to collaborative sequences that contribute to designing

At this and the following layer of analysis, we focused on team-level activities. In identifying whether and how each inscribing-event contributed to collaborative designing, it was necessary to consider neighbouring turns-at-talk, inscribing-events and other actions *for each collaborative inscribing-event.* To begin with, we recognised an underlying three-part sequential structure in the teams' interaction; an inscribing-event regularly conveyed meanings that observably linked it to the previous turn-at-talk and to the succeeding turn-at-talk. At various levels of granularity, similar sequential structures of human behaviour and interaction have been identified by, for example, Goffman (1964), Sacks, Schegloff and Jefferson (1974) and Enfield (2009). In our data, the length of a sequence was rarely limited to three parts; instead, several successive inscribing-events and turns-at-talk were commonly linked with the above-mentioned mechanism.

Jordan and Henderson (1995) noted that the turn-taking system, familiar from the tradition of conversation analysis, entailed not only talk but also all the modalities that people may utilise to take a turn (cf. Bucciarelli 1996, drawing as a speech-act). Contrary to our expectations, the situations in which an inscribing-event was linked directly to another inscribing-event—without any intermediating turns-at-talk—occurred only when production of a single inscription took over several inscribing-events and no change of scribe was involved. Therefore, no inscribing-events building directly on other inscribing-events—without any intermediating speech—could be recognised at this very detailed level of analysis. Another reason for this outcome may have been our setting; team members sat around a relatively small table, facing each other, and working under a time limit. An implicit expectation to actively share and discuss could have been in the air.

Next, having established the basic structure of a sequence—a unit of meaningful interaction—we filtered out the sequences that presented *active collaboration* and *contributed to designing*. We set two criteria:

1) *more than one team member contributes* to the sequence, either via one or more inscribing-events or via turn(s)-at-talk
2) each of those contributions *add significant value to the development of the design solution*. By 'significant value' we meant that the proposed idea was further enhanced, evaluated, explained or built on, rather than merely replicated or confirmed by 'ok', 'fine' or 'I agree'.

After that, we categorised the collaborative inscribing-sequences according to how they contributed to efforts to find a collective solution to the design task. Because our special interest was in explorative inscribing processes, we selected a data-driven categorisation that reflected *the purpose of the inscribing-event(s) within the sequence*, determined by how the inscription was *first* utilised: (1) explorative, (2) documentative or (3) regulative (Table 4). By using the concept of 'regulation' (Järvelä and Hadwin 2013), we wanted to reflect the multiple ways in which the teams utilised inscribing to actively negotiate, monitor and regulate goals, strategies, progress and emotions that affect the atmosphere.

Table 4 Categorisation scheme, collaborative inscribing-sequences

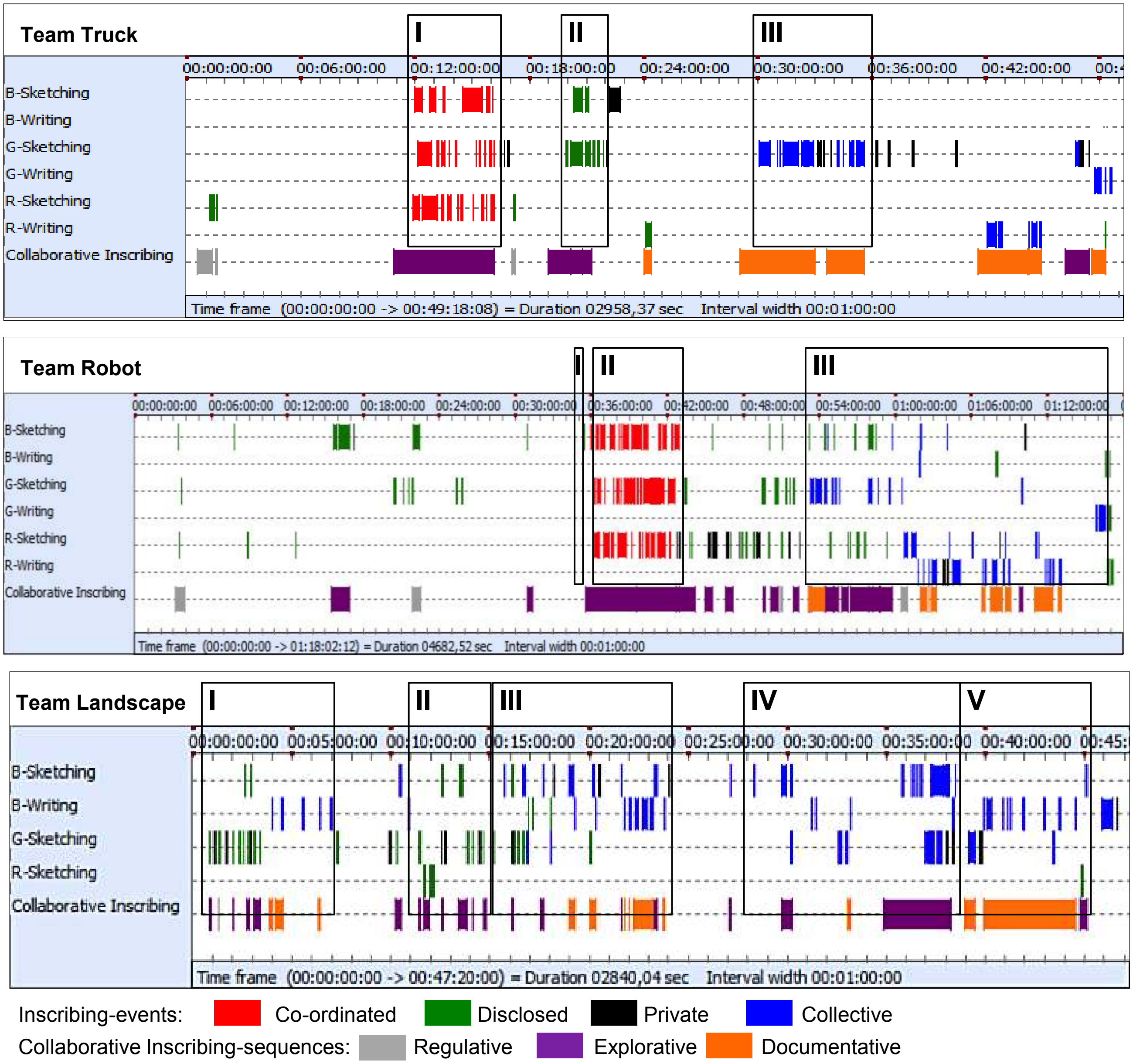
Categories	Explanations
Explorative	Inscribing to generate and evaluate ideas and solutions within the team.
Documentative	Inscribing to communicate design solutions to outsiders or for later use.
Regulative	Focusing on working practices and environment, turn-taking structures and regulation of the working atmosphere.

From sequences to advancing designing

In the third analysis layer, we focused on explorative and regulative sequences to examine how inscribing-events were linked with each other in promoting the accomplishment of a collective design solution. In our data-driven analysis, we tried both bottom-up and top-down approaches. Unfortunately, the bottom-up approach produced no clear results; starting from inscribing-events revealed no recurring patterns. With the top-down approach, however, we recognised three *functions* for explorative and regulative inscribing-sequences: (1) sketching a proposal, (2) sketching to further enhance a proposal and (3) sketching to regulate. When further refining the functions, we identified the following six *capacities of collaborative inscribing*: (1) sketching a proposal, (2) exploring with spatial and structural qualities, (3) incremental refinement of a feature, (4) adding a minor feature, (5) depicting constraints or ways of working and (6) regulating the working atmosphere.

Results

Below, we present timeline charts and thick descriptions of the teams' visualisation sessions, followed by results for each analysis layer. In the following timeline charts, the individual team members are referred to as R, G and B (red, green and blue), according to the colour-coded bracelets that team members wore during the video-recorded sessions. In addition, each team member's events of writing and sketching type appear in separate rows, and team-level sequences of collaborative inscribing appear in the bottom row.



Note: Inscribing-events of individual team members (B, G, R) appear in the top rows; sketching and writing events appear in separate rows. Inscribing-sequences appear in the bottom row.

Fig. 2 Timeline charts (from top to bottom): Team Truck, Team Robot and Team Landscape

Teams' visualisation sessions

Before the team session, team members individually completed the creative problem-solving task (as detailed in Fig. 1). Based on that task, team members carried new constraints (forms and themes) with them when they entered the team session. Due to these constraints, the teams had to revisit decisions made in the earlier session. Depending on the level of their earlier commitments, this caused more or less turmoil. We believe that because of the need to reconsider earlier solutions, the teams sketched more and their sketching processes showed more diversity.

Team Truck

Team Truck had no previous commitments to design solutions, and the new constraints were calmly accepted. In general, they had a highly regulated working process, with a clear division of labour. Team Truck began by negotiating goals and working practices; therefore, very little inscribing took place during the first quarter. Their inscribing process involved three phases with moves, testing and clear decision points. Initially, each team member selected one theme and, based on the selected forms, inscribed a proposal (Fig. 2: I, co-ordinated inscribing). Of the three inscribed proposals, Team Truck withdrew two: a building and an animal. The second round (II, disclosed inscribing) saw the further development of two parallel proposals of the third option, a vehicle, except this time the idea was developed verbally and sketching had a documentative role. Again, the team came to a decision and selected a truck with a trailer. Next, Team Truck switched to collective inscribing (III) to produce their final drawing. Long white periods in the timeline with no inscribing-events suggest that Team Truck executed significantly fewer inscribing-events than the other teams. In Fig. 3 on the following page, we can see that their final solution focused on structures and forms, with few refining features.

Team Robot

Team Robot's preliminary ideas from the previous session slowed them down in the beginning. The team negotiated how to continue with new constraints, without abandoning the premises and objectives set in the previous session; few attempts at disclosed inscribing actually progressed—moves mainly failed when tested. Halfway through the session, Team Robot reached a turning point (Fig. 2: I); the idea of a robot emerged in discussion. Each team member inscribed a proposal (II: co-ordinated inscribing) and then began negotiating the details. This type of collaboration (co-ordinated followed by disclosed inscribing) was similar to Team Truck's (in Fig. 2: II + III). The development of a collective solution (Fig. 4: III), however, was organised differently; one team member at a time was responsible for inscribing the collective solution while the others sketched their suggestions for sub-solutions. These suggestions—moves—were then collaboratively tested in conversation, and if the sub-solutions passed the test, they were incorporated into the collective solution. A number of details (e.g. eyes, legs, mouth, Velcro fastenings; see Fig. 4) were developed in this way, by iterating (disclosed inscribing cultivated collective inscribing), using both documentative and explorative inscribing. Based on the distribution of inscribing-events across the team members, Team Robot's division of labour seems more symmetrical than Team Truck's. Team Robot's volume of inscribing-events is substantially higher than Team Truck's. In the last half of the session, inscribing-events were more evenly distributed, with no long gaps between events; for Team Robot, inscribing was a regular activity in developing the collective solution.

Team Landscape

Team Landscape soon discovered that the selected themes permitted them to continue with their previous idea of a landscape. That allowed the team a quick start in ideating how the forms could be used for compositional landscape elements, such as trees, mountains, a cottage and a pond (Fig. 2: I), by using collective and disclosed inscribing. Because they saw no need to revisit their previous commitments, they had no obvious reason for ideation by co-ordinated inscribing but were able to choose one team member to serve as the main scribe. Soon, the issue of the forms and structures of the puzzle arose, and Team Landscape used the given forms as decision-making tools. They agreed on a geometrical structure for their puzzle (II) and summarised ideas to that point into a collective drawing (III). Next, they sketched and negotiated key measurements for the base structures (IV, which included measuring and inscribing) and finally, produced a schematic drawing that tied together elements and structures—a master plan (V). They produced three drawings, two of which (Fig. 5) could be considered final drawings. While the division of labour was less symmetric than in other teams, the inscribing-events were more evenly distributed across the timeline.

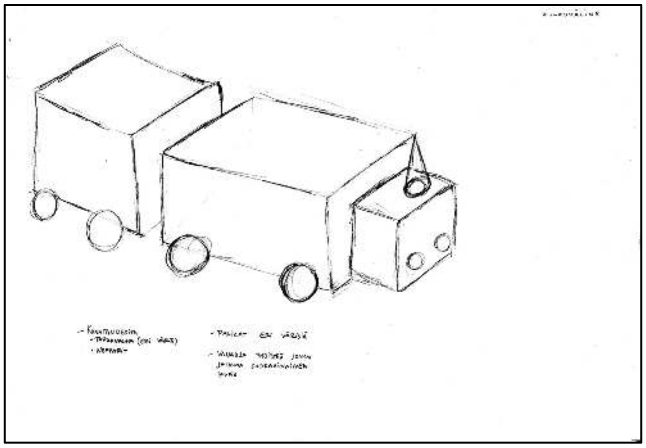


Fig. 3 Final drawing: Team Truck

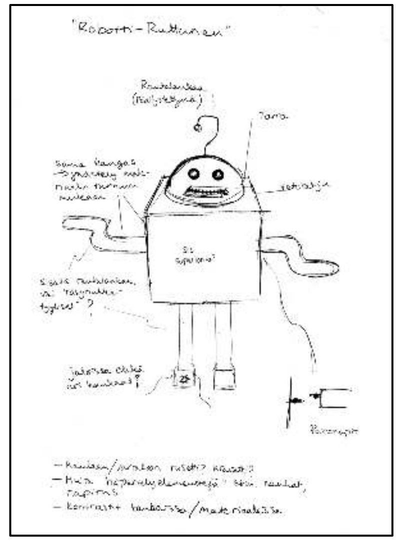


Fig. 4 Final drawing: Team Robot

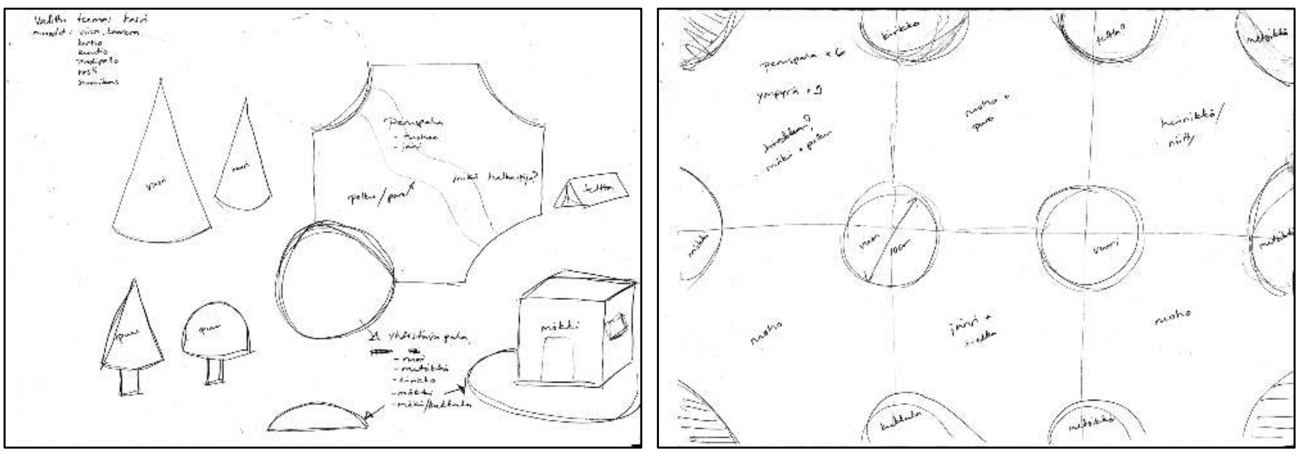


Fig. 5 Two final drawings (from left to right): Team Landscape's Landscape elements and master plan

Event-layer results: ways of collaborative inscribing

Different ways of inscribing as a team—ways of collaborative inscribing—are shown graphically in the timeline charts (Fig. 2). Three characteristics of how the teams utilised collaborative inscribing are discernible in the timeline charts: the division of labour, the amount of inscribing and the distribution of the inscribing-events across the session. These in turn indicate *the symmetry of participation, the nature of inscribing as a tool and the extent to which the teams' idea development and designing was dependent on this tool.* According to the charts, team members each contributed to designing by inscribing. While symmetrical participation with a shared object of attention is characteristic of collaboration, some degree of division of labour should emerge when granularity increases (Dillenbourg 1999). At times, division of labour was pre-negotiated and regulated. *More frequently,* *however, inscribing and the division of labour were less regulated and emerged as the design conversation progressed*.

Table 5 Ways of collaboration: frequencies of categorised events

Ways of collaboration	Team Truck		Team Robot		Team Landscape		Total	
Co-ordinated	28	32%	52	29%	0	0%	80	21%
Collective	28	32%	50	28%	67	58%	145	38%
Disclosed	16	19%	59	33%	31	27%	106	28%
Silenced	15	17%	18	10%	17	15%	50	13%
Total	**87**	**100%**	**179**	**100%**	**115**	**100%**	**381**	**100%**

Table 6 Nature of inscribing: frequencies of sketching and writing-type events

Nature of inscribing	Team Truck		Team Robot		Team Landscape		Total	
Sketching	71	82%	146	82%	80	70%	297	78%
Writing	16	18%	33	18%	35	30%	84	22%
Total	**87**	**100%**	**179**	**100%**	**115**	**100%**	**381**	**100%**

According to the timeline charts and Table 5, Team Truck preferred discussing to inscribing, while members of Team Robot all inscribed actively. Team Landscape occupied the middle ground, with one team member appearing as the main scribe. In Table 6, while co-ordinated and collective events together represent more than half of all the teams' events, private events were in the minority, which implies the collaborative nature of the teams' inscribing.

Sequence-layer: ways of contributing to designing

Sequence-layer analysis identified how events were linked to form sequences, and our categorisation—the ways in which the sequences contributed to designing—emphasised the purpose of inscribing-event(s) within the sequence. Table 7 summarises the results, which also appear in the timeline in Fig. 2 (bottom row, *Collaborative Inscribing*).

Table 7 Collaborative inscribing sequences categorised by purpose

	Team Truck		Team Robot		Team Landscape		Total		Total
	Sketching	Writing	Sketching	Writing	Sketching	Writing	Sketching	Writing	
Explorative	4	0	17	0	19	0	40	0	40
Documentative	2	4	3	7	3	9	8	20	28
Regulative	3	0	5	0	1	0	9	0	9
Total	**9**	**4**	**25**	**7**	**23**	**9**	**57**	**20**	**77**

In total, inscribing mediated the collaborative exploration, documentation and regulation of activities for all the teams. *More than half of all sequences were explorative*, and *all explorative sequences were of the sketching type*. On the other hand, all sequences of the writing type were documentative. This highlights the different roles of sketching and writing in these data; In many cases, *sketching substantiated the idea, so providing detail and precision, but writing merely transcribed the ideas already expressed in the turns-at-talk.*

The timeline charts (Fig. 2, Collaborative Inscribing row) show that *the teams had certain ways that were characteristic of them, which revealed the mediating role they assigned to inscribing*. Team Truck produced one final drawing, a re-production of a previous sketch; their style was 'first explore, then document'—a long cycle. Team Robot also produced one final drawing, but with frequent exploration between documentative sequences, a style of 'explore-document-explore-document' not seen in other teams. Team Landscape, on the other hand, had three clusters of documentative sequences and produced three collective drawings. Their style changed from 'exploration initiated by inscribing' to 'exploration initiated by discussion'; the tool-like nature of inscribing changed from an instantiation tool to a substantiation tool. To conclude, *inscribing—and especially sketching—was a tool for all the teams to explore features and solutions, to document the team's collective solution and to regulate the team's collaboration, in that order.*

Advancement-layer: kinds of collaborative sequences that advance designing

In the third analysis layer, we further examined explorative and regulative sequences to understand the kinds of sequences that advanced the accomplishment of a collective solution. In our method, sequences represent instances *where* inscribing mediates, and the kinds of sequences show *how* this mediation advances the efforts of collaborative designing. Our data-driven analysis identified three functions and six capacities (Table 8).

Table 8 Functions and capacities of collaborative inscribing

Functions	Capacities	Team Truck	Team Robot	Team Landscape
1. Inscribing a proposal				
	Inscribing a proposal	2	8	9
2. Inscribing to further enhance a proposal				
	Exploring with spatial and structural qualities	2	4	8
	Incremental refinement of a feature	0	3	1
	Adding a minor feature	0	2	1
3. Inscribing to regulate				
	Depicting constraints or ways of working	3	4	1
	Regulating the working atmosphere	0	1	0

The following paragraphs characterise the above-mentioned capacities. Two data excerpts are provided to illustrate capacities with *explorative cycles of inscribing and speech, moving and testing*. These excerpts also function as examples of exploration-type collaborative sequences.

Inscribing a proposal

Inscribing a proposal means that a proposal is substantiated for the first time. This was the most common capacity, and in our data, all proposals but one were based on the given forms and themes (that is, on external design constraints) or on the Celia guidebook for making a tactile book. In this capacity, the type of inscribing-event—disclosed or co-ordinated—related to the complexity of the proposal. While disclosed inscribing produced proposals for details and structures, long (5–7 minutes) sequences of co-ordinated inscribing produced proposals for puzzles.

Inscribing to further enhance a proposal

Once proposals were first inscribed, they could then be further enhanced. In our data, enhancing most often meant *exploring with spatial and structural qualities*, that is, with 2D or 3D properties and possibilities. This feels natural, as inscribing is a more powerful tool than speech for demonstrating and evaluating these qualities. The second type of capacity, *incremental refinement of a feature,* consisted of several inscribing-events: the first of which substantiated the idea and was often followed by events that enhanced, reinterpreted and newly substantiated to the idea, finally ending with the idea incorporated into the final inscription. In this capacity, the first inscribing-events were disclosed, and the last one was collective. The third capacity to enhance a proposal was *adding a minor feature*, which usually included only one (disclosed or collective) inscribing-event.

Exploring with spatial and structural qualities was a typical capacity for Team Landscape, due to their self-imposed constraint (Lawson 1997): a structure that supported multiple ways to arrange the pieces. The following Excerpt 1 captures Team Landscape in the process of developing their key structural idea: a two-layer structure.

Excerpt 1: Team Landscape discovers two-layer structure

Prior to this sequence, Team Landscape had already toyed with the idea that the landscape elements could entail a common base structure, some specific form. However, the challenge of how to combine the pieces still remained.

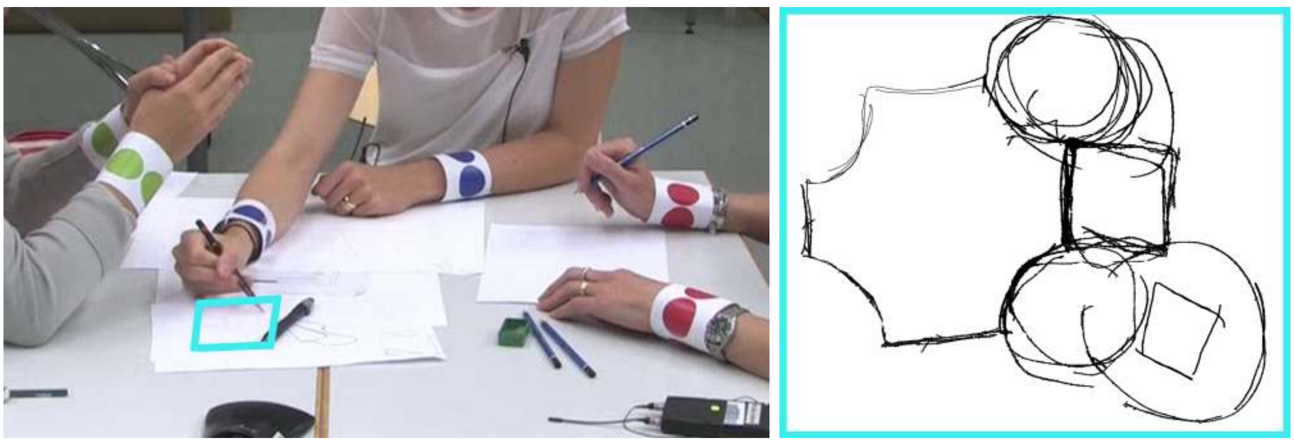


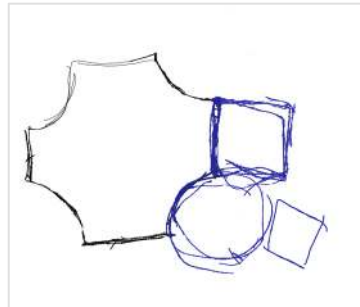
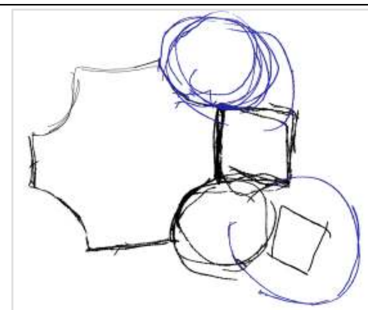
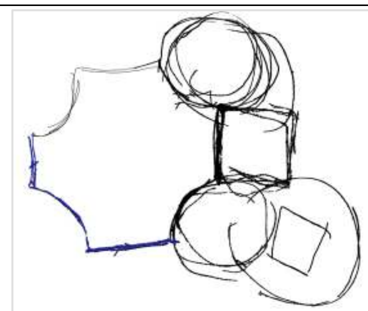
Fig. 6 On the left is a screenshot from the side-view camera, in which the relevant working area is demarcated in blue, and on the right is the finalised section that Team Landscape was working on

Key for Tables 9 and 10

Transcript:
(.) short pause
(beginning of an action
) end of an action
(sketches……..) period of sketching
[ ] explanations added by authors

Sketches:
newly inscribed content in blue
previous content in black

Table 9 Transcript and produced sketches for Excerpt 1

#	Team member	Transcript	Sketch (produced lines in blue)
2.1	L_Blue	So do we then use, do we use these multiple forms [to create a cabin, refers to forms that the team selected from the given forms, in the beginning of the visualisation session] (sketches a rectangle ……….) (sketches a circle and a rhombus......) so that there is one like this (.) or is this cabin also on this kind of a round base, like this	
2.2	L_Green	(interrupting L_Blue) Yeah, that's what I just	
2.3	L_Blue	(makes several circular pointing movements on top of the circle) like this, that these are always (.) always, it's like	
2.4	L_Blue	(sketches a second circle around the rhombus) You can always put it there or (sketches a third circle) you can put it there and (makes a circular pointing movement on top of the second circle) you can put a mountain there or like that, do you reckon.	
2.5	L_Green	Yeah, so that's what I, that's what I was thinking, too, that, do we have there like (.) If the elements like the tree, if they are (re-draws the edges of the rectangle with inverted rounded edges) like in principle, on the same kind of platform, always.	
2.6	L_Red	Mmm	
2.7	L_Blue	Mmm	

This excerpt from Team Landscape shows how L_Blue instantiated two proposals by sketching (2.1)—two moves for herself and the others to evaluate—to use a rectangle for the cabin, or to place the cabin, and also other landscape elements, on a round base element. In her next sketch (2.4), L_Blue explained, expanded and tested her first proposal: if the landscape elements were placed on a circular base, the created puzzle structure would support interchangeable pieces. L_Green further expanded her teammate's suggestion verbally (2.5): to always use similar platforms as bases for landscape elements, such as trees, mountains and cottages. L_Green's sketching-event (2.5) involved re-drawing, emphasising a previously proposed form (a rectangle with rounded inverted edges). This sketching-event introduced no 'new' information to the conversation, but it emphasised the co-occurring message conveyed vocally (2.5).

Excerpt 1 is a typical example of how sketching mediated solving spatial and structural challenges. The previous sketch of the agreed base structure provided a memory extension, and adding the new proposals into that sketch made it easy to evaluate the options the team had. Sketching served as an instantiating tool (Table 9, 2.1), as a substantiation tool (Table 9, 2.4) and as a rhetorical tool (Table 9, 2.5). As typical of Team Landscape, little explicated evaluation or challenging appeared; they often reached an agreement instantly.

Excerpt 2: Team Robot, incremental refinement of the robot's mouth

The next excerpt offers another example of enhancing a proposal, which illustrates a capacity typical of Team Robot: incremental refinement by inscribing—in this case, the idea of a robot with a zipper as its mouth. Sections where the team members worked are highlighted in Fig. 7 and appear in Table 10 as follows:

R = R_Red's proposal, sketched during 3.10–3.12 (Fig. 7 and Table 10);
B = (a part of) R_Blue's proposal for a robot, sketched prior to this sequence during the period of coordinated sketching (Fig. 2: II);
C = (a part of) the team's collective solution and
F = forms given as part of the task instructions.

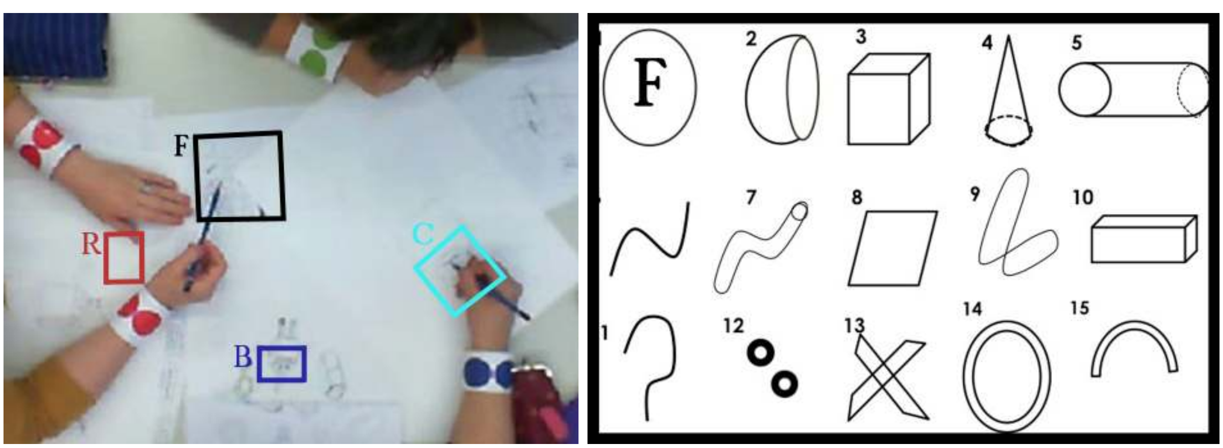
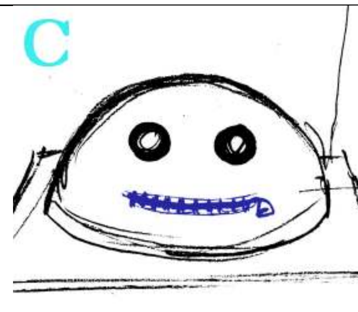
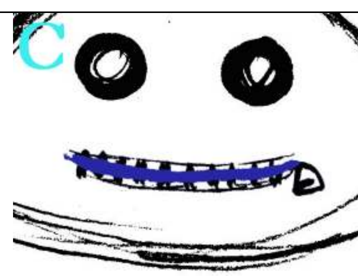
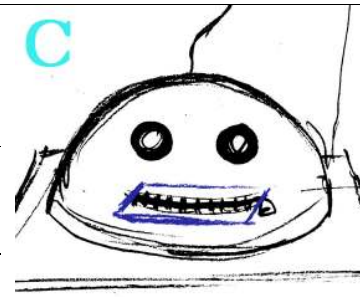


Fig. 7 On the left is a screenshot from the top-view camera showing the relevant working areas R, B, C and on the right, the given forms F

At the beginning, R_Green was still finalising the robot's head—a part of the team's collective solution (C) —when R_Blue initiated a new collaborative sequence regarding the robot's mouth.

Table 10 Transcript and produced sketches for Excerpt 2

#	Team member	Transcript	Sketch (produced lines in blue)
3.1	R_Blue	(background: G is sketching, finalising robot's head …… …………) (re-draws the mouth of a sketch produced earlier) Here comes its mouth and teeth	
3.2	R_Red	(replies to R_Blue) So the mouth	
3.3	R_Green	(interrupts R_Red while simultaneously sketching the mouth ……) These [the mouth and the teeth] are, aren't they [the forms] ours, or did we already pass over [the forms in the instructions]?	
3.4	R_Red	(pointing to form 8, a parallelogram, in the instructions F) So I'm thinking that the mouth, the mouth can be (.) in a way (.) like, we can try to	
3.5	R_Green	(interrupting R_Red) Oh yes. Did we pass over [the instructions] – Right.	
3.6	R_Blue	(simultaneously with 3.5, re-draws the mouth of collective solution ……………………………) Yeah, here's a mouth, here.	
3.7	R_Red	But no, we didn't [pass over]. I think that	
3.8	R_Green	Yeah	
3.9	R_Red	(pointing at the mouth in the collective solution) I mean it's just fine [like it is now]	
3.10	R_Red	(sketches …………………………………………………..) But I'm thinking that it can be, if we want to, like do in a way, like that	

3.11	R_Green	mmm	
3.12	R_Red	(sketches ………………) (points at form 8 in F) If you want to use that form over there (continues to sketch …….) then in a way it is like this	
3.13	R_Green	(sketches …………………………... So [the place] where the zipper is [a 'legitimate' form], it [the ………………………………………………………………… zipper] is just like its [a detail inside the 'legitimate' form]	
3.14	 R_Red	(R_Green continues to sketch ………………………………… 'Cause it is in any case an area of its own (.) probably a cloth of some colour, maybe.	
3.15	R_Green	(continues to sketch .... Yeah, well, it can be ………………………………………………………………)	
3.16	R_Red	And, this is a sketch. I dunno what we'll then really be really doing.	
3.17	R_Green	Yeah.	
3.18	R_Red	Yeah.	

This incremental refinement began with R_Blue making a move by re-drawing her previous proposal for the mouth (3.1) that looked almost like Lego bricks. R_Green made another move: sketched a mouth and teeth (3.3) into the collective solution, and substantiated her idea, a zipper-mouth with a zipper lock on the right. As the substantiation concretised the requisite forms, it caused her to doubt whether the zipper agreed with the 'legitimate' forms (3.3–3.5 and 3.7–3.9). Meanwhile, R_Blue implied her consent by re-drawing the line of the zipper mouth (3.6). However, R_Red had a solution to the problem of the non-legitimate form: a reinterpretation that combined R_Blue's proposal, R_Green's zipper idea and form 8, yielding a zipper inside a parallelogram which was a 'legitimate' form (3.10 and 3.12). In this way, R_Red provided a third substantiation to the robot's mouth. R_Green noticed that this enhanced proposal shared sufficient coherence with the constraints—passed the test—and she incorporated it into the collective solution (3.13–3.15), giving a fourth substantiation to the robot's mouth.

In this excerpt, all team members participated actively, and sketching was the key vehicle in advancing the development of the solution; first, the ideas were sketched, and then, rather indexical verbalisations followed. Sketching served as an instantiation tool (Table 10: 3.3; 3.10; 3.12) and a rhetorical tool as well as a tool for validation (Table 10: 3.1; 3.6) and substantiation (Table 10: 3.13–3.15). In addition, team members evaluated (Table 10: 3.6; 3.9; 3:13) and reinterpreted each other's sketches (Table 10: 3.10; 3.12). Cycles of sketching, reinterpretation and evaluation supported the team's iterative efforts to create a mouth for the robot that agreed with the 'legitimate' forms.

Inscribing to regulate

Two distinct regulative capacities emerged: *depicting constraints or ways of working* and *regulating the working atmosphere*. All the teams depicted constraints by marking the given forms or decisions on paper for everyone to see at a glance. Regulation of the working atmosphere, on the other hand, occurred only in one team: Team Robot (cf. Hope 2008, drawing to express humour). All in all, regulative capacities contributed indirectly to the design solution, playing *an important role in securing collaborative work and supporting explorative ideation.*

Discussion

Within the setting of collaborative designing of a 3D puzzle, we analysed the student teams' sketching processes from two vantage points: how sketching processes reflected collaboration and how epistemically meaningful actions of sketching contributed to the advancement of a collective design solution. We posed three research questions: (1) What ways of collaborative working are reflected in actions of sketching? (2) In what ways do sequences of collaborative sketching contribute to designing? (3) What kinds of collaborative sequences of sketching advance designing? To answer these questions, we analysed three layers of sketching: micro-level actions, that is, inscribing-events; sequences of events and linked speech; and sequences that advanced designing. In our analysis, based on the elementary building blocks of the sketching process and the epistemic meanings they were assigned in the designing conversation, we used INTERACT video analysis software, and especially its graphical timeline view.

Our analysis shows that sketching mediates collaborative working in three distinct ways. First, in collective inscribing, the team's designing efforts culminate in one drawing—a single outcome (cf. Hennessy & Murphy 1999)—that represents the team's creativity and knowledge. Second, co-ordinated inscribing represents a regulated working process in which ways of working are negotiated and agreed—a characteristic of collaborative interaction (Dillenbourgh 1999). Third, disclosed inscribing, where the idea is first sketched and then discussed with the team, represents interactivity—another characteristic of collaboration, (Dillenbourgh 1999). Additionally, sketching facilitated mutual appropriation (John-Steiner 2000) in which team members sketched reinterpretations and verbally proposed new features as add-ons to each other's sketches. Luckily for collaborative sketching, this is contrary to the results of van der Lugt (2005). Despite our detailed analysis of collaboration, we do not wish to imply that the teams' processes were more or less valuable or collaborative; rather, we aim to demonstrate that *different aspects of collaborative work are observable in and demonstrated by the teams' ways of sketching.*

Within the teams, solutions were explored and shared, sometimes in larger chunks—such as a proposed idea for a puzzle—and sometimes feature by feature or even line by line. In our data, all three ways in which sketching supports exploration, as identified in the design research literature, were present. Sketching provided an extension to memory; team members regularly referred to older sketches or features sketched earlier. Sketching also supported iterative efforts of producing ideas and provided a tool to evaluate and test the sketched ideas. Each team used sketching actively to advance designing. 'Explorative' was the most frequent type of sketching-sequence, and as our analysis of functions shows, 'New proposals' were almost as frequent as 'Enhancements to previous proposals'. These results underline how, beyond a mere technique, *the teams employed sketching as a meaningful tool to produce a design solution*. However, sketching was not their only tool. White gaps in teams' timelines do not indicate silence or off-topic activities but rather designing that relied on another tool important in designing—language.

In our setting, the new constraints—forms—brought to the table at the beginning of the visualisation session most likely influenced the teams' processes. These forms induced a need to revisit and test previous commitments. In addition, it was far easier to test whether the proposed ideas fulfilled the constraints, forms in 2D and 3D, by sketching than by describing the ideas verbally. In the end interviews, the teams reported that the forms helped them to reduce and simplify their puzzles; as Team Landscape stated, 'without the forms, only the sky would have been the limit'. To conclude, the teams' sketching processes showed more diversity and richer content, and the puzzles were more streamlined due to the introduction of forms at the beginning of the session.

Our contribution to the discussion of whether or not students benefit from sketching is that of the four teams in the initial setting, the three included in our analysis clearly benefited from sketching. Team Truck produced their three main proposals (a building, a vehicle and an animal) through co-ordinated inscribing; Team Robot constructed many important features of their robot (eyes, mouth, legs, Velcro fastenings) through incremental refinement, which combines both disclosed and collective inscribing; and Team Landscape used collective sketching throughout the session to explore and to create a two-layered geometrical structure for their puzzle. *Sketching led to invaluable advances in designing for the three teams, but in different ways*. In that basis, the instructions should allow for multiple ways of organising sketching.

Naturally, our micro-level analysis method has some restrictions. While sketching is performed part by part (Kavakli et al. 1998) and designing proceeds iteratively (Authors 2001), those parts and iterative cycles form longer cycles of idea development. Micro-level analysis does not, as such, recognise macro-level activities. At times, the iterative development of key features and structures occurred over several sequences, and those sequences were distributed across the design session. Our analysis recognises the sequences, but the mechanism for combining sequences that iterate the same structure would require further analysis. However, considering our research questions, the risk involved was minimal. Additionally, a macro-level analysis of the teams' design processes is reported in another study (Authors 2016a), offering insights into the above-mentioned longer cycles. Our method can be used in future studies of multimodal interaction, especially when investigating modalities of an elusive nature or brief events.

While we continue to stress that students as well as craft teachers need to learn the value of sketching as a vehicle for designing (see Authors 2014), *we also acknowledge the significance of other design tools.* Our previous study (Authors 2008) stressed the need to use multisensory sources of inspiration, and another study of ours (Authors 2016b) highlighted the strengths of 3D modelling techniques, particularly in comparison with the sketching technique. Instead of committing to one single tool, we see that different tools have different affordances and different implications for students' design processes—and as design teachers we should carefully consider the implications of our choices and of the assignments we set for students.

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