Design Tools for Supporting the Remote Collaborative Design Process: A Systematic Review

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ABSTRACT

As design collaboration shifts from co-located to remote, both human-computer interaction (HCI) and Computer-Supported Cooperative Work (CSCW) have been seeking ways to support distributed collaborative design processes. We noticed that a lot of studies focused on the early phase co-ideation process, i.e., brainstorming and sketching, while the later phase co-exploration through iterative prototyping remains relatively unexplored. Therefore, improving the remote collaborative design process remains a research challenge. This literature review elaborates on the current supporting tools and their corresponding strategies during different design practices. We contribute an overview of the design space for improving the remote collaborative design processes. Moreover, we identified gaps and opportunities for future research and tool development in the remote collaborative design process. We end this paper by concluding the insights with a research agenda for our future research.

CCS CONCEPTS

• Human-centered computing; **• Collaborative and social computing**; **• Collaborative and social computing theory, concepts and paradigms**; **• Computer supported cooperative work**;

KEYWORDS

literature review, supporting tools, remote design collaboration, prototyping process, physical prototype

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1 INTRODUCTION

Designers collaborate during the design process. They share expertise, bring different skills, establish a shared understanding, and explore together to accomplish design tasks. Research on supporting tools for the distributed collaborative design process has an increasing popularity in both human-computer interaction (HCI) and Computer-Supported Cooperative Work (CSCW) fields. For instance, shared whiteboards for co-ideation [19, 42, 62, 63, 69], shared prototyping platforms for co-making digital models [5, 31, 90], shared augmented-reality (AR) spaces with different visual communication cues [6, 46, 47, 88], etc. These tools focus on using mediated approaches to achieve a real-time collaborative design process, similar to what they would experience when working in a co-located environment.

However, the full richness of design ideas cannot be transferred properly by any mediated approaches yet. In previous research [103], we found many problems that negatively influenced the distributed collaborative design process, for instance, lack of proper means for communicating ideas of interaction [103], missing awareness of the activities of the remote collaborators [7, 68], and difficulties in effectively critiquing physical prototypes [65]. In a domain such as industrial design, prototypes play a vital role in supporting creativity and innovation [60, 75, 79]. Throughout the design process, designers often engage in several iterative cycles of exploration, using many different kinds of prototypes, such as sketches, mock-ups, models, and working prototypes [91]. We noticed that a lot of studies focused on supporting the early phase of the co-ideation process, i.e., brainstorming and sketching [22, 67, 86]. The later phase of co-exploration through iterative prototyping process remains relatively unexplored.

In this paper, we reviewed recent tools that aim at improving remote design collaboration, particularly the prototyping process. We carried out a systematic literature review with the following objectives:

- To understand the current tools with corresponding design activities during the iterative prototyping process.
- To understand the tool's design strategies and find the gaps for improvement.

This review is structured as follows. We begin with a brief tailored review as background (section 2) to understand both co-located and remote collaborative design processes. We identify designers' needs from literature and frame their corresponding design strategies for supporting remote design collaboration. This tailored review is done to inform the selection criteria for the main literature review, which starts from section 3. We explain the methodology of our main review following PRISMA guidelines. In section 4, we present the data in charts and briefly summarize our findings. Section 5 goes more in-depth. We elaborate on the patterns that we found, as well as map out gaps and opportunities for future research and tool development in the remote collaborative design process. Finally, we conclude this paper with a research agenda consisting of three topics: 1) designing tools for supporting shared experiences during the collaborative design processes, 2) extending the research

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studies involving more phases of co-exploration, 3) considering conducting more structure-based design experiments and applying more design-related evaluation criteria.

2 BACKGROUND

Our inquiry starts with the assumption that the design process is comparable in both co-located and remote collaboration contexts. This means that we assess tools in accordance with the co-located collaborative design process and utilize it as a model for the remote collaborative design process. Therefore, we first investigate what designers need from the tools during co-located design collaboration. Then we explore the trend of remote design collaboration to understand emerging problems and opportunities. In the last step, we synthesize the insights from the first two steps together and identify design strategies for supporting remote collaborative design processes. The outcomes of this tailored review, namely the four design strategies, serve as our selection criteria for the systematic literature review.

Co-located design collaboration Physical proximity has been studied in the literature as a factor influencing collaboration [78]. Within the field of industrial design, especially (interactive) product design, designers usually collaborate with each other in a geographically co-located context. Physical proximity provides the advantage of being aware of one another's status quo and allows for the development of a shared understanding of the shared design challenge [50]. Through observing how designers collaborate within co-located design studios, Vyas [95] noted that exploration plays an essential role during design collaboration. We chose to focus on the explorative phases of the design process including the ideation and prototyping process [30]. The exploration phase and its techniques, e.g., brainstorming, developing interaction mechanisms and testing prototypes, encompass experiential, creative, and inspirational interactions among designers [8, 15, 82, 92]. Throughout the exploration process, designers apply various design activities to stimulate creativity. They question one another, and the questions are often not intended to engage a solution, but rather to fill in details in order to establish a shared understanding of the design challenge among the team [85]. We investigate designers' needs during a co-located collaborative design process to better understand the supporting strategies behind different tools. Several previous studies identified different features of design collaboration. Tang [87] identified five features of collaborative activities that should be taken into account when designing collaboration tools: gestures, spaces, the process of collaborative drawing itself, the mix of simultaneous activities, and the spatial orientation of co-workers. Scott et al. [80] identified four user requirements for collaboration: accessing and use of the objects, interaction between users, transitions between activities, between individual and group work, transitions between spaces, and simultaneous user interactions. Vyas et al. initially identified three characterizations of collaborative design practices [91]: externalization, use of physical space, use of bodies. They later reformulated these themes into: use of artefacts, use of space, and designerly practices [95]. We found patterns and mechanisms that are catalyzing design collaboration and we distilled these into four needs of designers in collaborative design processes:

A need for prototypes in different levels of fidelity (N1) Prototypes play a pivotal role in supporting communication and co-creation during the design process [60] aided by the richness of the material artifacts [41]. They evoke a focused discussion within teams [79] and help designers to go through iterative cycles of exploration to reach concrete design ideas [20]. At different stages in the exploration process, they use sketches, mock-ups, models, working prototypes, and so on [8, 26, 92].

A need to express bodily actions (N2) Our bodily movements convey emotions as well as geometry and interactions [38] and this is used as a powerful technique for design exploration. By using bodily actions, designers gain a better understanding of the design task and at exploring new possibilities [9, 51, 95].

A need for different types of spaces (N3) Designers require different types of spaces during design collaboration. Spaces are not only for organizing their projects during the design process, but also for sharing them with coworkers [94]. These spaces help designers to discuss and modify design content more easily, allowing them to refer to specific design phenomena and leave signs of their actions even when not all members are present [87, 92, 93].

A need to engage in creative social practices (N4) Designers employ a large set of collaborative methods and approaches to construct new design ideas, such as co-creation [27], co-making [50], co-reflection [89], etc. Creative social practices contain an iterative process of creating and reflecting [76]. By designing together and co-reflecting in- and on their work, designers establish common ground, build on each other's ideas, and thus get a broader and deeper grasp of the solution domain [95].

Remote design collaboration We first investigated the common assumption that designers collaborate better face-to-face, and hence that the collaboration suffers from being distributed. Hammond et al. [33] found that, although designers spent more time collaborating in a distributed collaborative design process, they produced fewer design alternatives. Eris et al. [22] indicated that, compared to a co-located design team, remotely collaborating designers were less likely to use gestures, instead, they spent more time on drawing. Also, they participated in fewer studies and discussions about the design problem. Kvan [53] and Cross [18] argued, that this could even lead to designers compromising design decisions, prohibiting them from finding the best solutions. On the other hand, other research has presented findings that contradict the assumption. Tang et al. [86] indicated that, when comparing the outcomes from a co-located and a distributed design team, the design process showed no significant differences. Adding evidence, Mulet et al. [67] demonstrated that the degree of novelty was very similar in both conditions. Moreover, according to Rice et al. [77], distributed teams can more effectively brainstorm, create documents, confirm decisions, and negotiate how to proceed.

We tried to understand these very different conclusions from the literature around the effectiveness of distributed collaboration. The explanation is that the studies that found no differences between co-located and distributed design collaboration, have employed controlled and brief studies focused on either the early design ideation or the decision-making process in the computer-mediated collaboration teams. Participants in these studies joined in the group activities likely the same as general users in the CSCW field. Their design practices and outcomes revolved around sketches and text descriptions. Even when the design focused on interactivity, physical prototypes and iterative prototyping processes were not considered. Therefore, we question if the studies on both sides investigated the same phenomenon as they framed the design process very differently.

At present, design practice is experiencing change. We observe that more and more design studios are engaged in distributed collaboration mediated by digital means. Unlike co-located collaboration, designers often can't or do not explore together anymore. Looking at the literature with its corresponding phases, we found only a few tools aimed at supporting distributed collaborations with (physical) prototypes. This issue was further exposed due to the global pandemic because designers were dramatically forced to shift to remote collaboration without sufficient preparation. Observing and surveying designers during the pandemic [103] corroborates the current status of the supporting tools: although certain designerly practices were less negatively influenced by remote working, some phases, particularly the (physical) prototyping process, lack appropriate tools.

Supporting remote design collaboration As we mentioned before, designers have a need for prototypes in different levels of fidelity *(N1)* during the design process. Similarly, designers often use their bodily actions *(N2),* i.e., 'point at' certain things, or to demonstrate their ideas of interaction. Besides, different types of spaces *(N3)* and creative social practices *(N4)* also provide opportunities for designers not only to present their work but also for inspiring each other during co-exploration. However, current studies show that these four needs are not properly met when designers work together during remote collaborative design processes. Therefore, we formulated four corresponding design strategies to improve remote design collaboration, which were used as our inclusion criteria for selecting papers:

1. Improving the prototyping process (S1)

Design is a co-evolving process in which problems and solutions change iteratively [101]. After reviewing 300 articles of empirical design studies about prototypes, Camburn et al. [11] pointed out that it is critical to prototype multiple iterations. The strategy of improving the prototyping process does not only include accelerating the prototype production [72, 98], but also includes concepts like reusing the prototypes into finding new design spaces [66], synchronizing the prototyping process between digital and physical worlds [57, 97] and improving the experience of collaborative prototyping [83, 84]. We also investigated tools that aim at improving individual prototyping processes if these could arguably augment the collaboration process and encourage co-exploration.

2. Making bodily actions visible (S2)

By introducing the Design Movement approach, Hummels et al. [38] demonstrated that bodily actions work as a design technique since they convey emotions, geometric information, and ideas of interactions. Buchenau M. and Fulton Suri J. [9] indicated that the vividness of using different bodily patterns and exploring different possibilities helps designers to make better design decisions. Kim et al. [45, 47, 56] investigated sharing various bodily actions through Mixed Reality (MR) techniques. They combined gestures, pointers, eye gaze, and sketches during remote collaboration. The results showed that the participants achieved fast completion times and a high level of co-presence. We investigated the tools claimed for improving shared bodily actions in general CSCW, since the design process also contains various bodily actions, thus these tools can possibly be applied to remote design collaboration.

3. Providing different use of spaces (S3)

Seeing the same object is necessary when designers work in a distributed fashion, as well as being around each other but looking at different things [25, 65] Research showed that with an independent view (e.g., shoulder by shoulder [10] or an out-of-body view as a ghost [43]), participants could understand the remote spatial situation easier than through the dependent view. Except for their actual spaces, designers also share working spaces that are more conceptual, i.e., artful surfaces [94]. For instance, Helaba [61] supports recording design rationale and decisions in a shared workspace, while ReflectionSpace [81] provides better support for recalling and communicating about the design process, decisions, and related resources. Designers present their spaces and surfaces related to the ongoing design projects and encourage each other to collaborate. All different spaces together construct the atmosphere with the full richness of visual information so that designers could absorb themselves in a certain project.

4. Encouraging creative social practices (S4)

Frich et al. [27] offer an overview of Creativity Support Tools (CSTs) and their potential. They found that there are some off-the-shelf digital technologies for helping designers accomplish their creative tasks, such as Adobe Creative Suite [2] and 3D modeling software Autodesk Fusion 360 [5]; However, most of the CSTs for design collaboration often never leave the labs in which they were created and don't have sufficient support for remote co-exploration. We found that while distributed remote collaboration cuts off the physical connection, it also limits the possibility of having effective creative social practices. Therefore, the last strategy that we identified is encouraging creative social practices among designers in the remote collaborative design process.

3 METHOD

3.1 Literature search strategy

We encountered hardware and software from the fields of engineering and computer science [35], as well as design interventions and conceptual frameworks from HCI [73, 100]; similarly, various types of workflows and collaboration methods from CSCW [21, 58]. Due to the multidisciplinary nature of the topics covered, we used a two-step method: first a systematic review by means of a directed search, and a follow-up snowballing based on the findings to also include different repositories. We first carried out a systematic literature review [49] that covered papers written in English and published between January 2013 and December 2021. We chose to use the ACM digital library as a starting point, since it is a large library with many relevant categories of work (e.g., CSCW, Collaborative and Social Computing, etc.) that offer a sufficiently broad perspective for our review. A Boolean search string (see Table 1) was developed across two categories of keywords: prototype and collaboration. To fill gaps in our overview caused by limitations in the ACM database or limitations in our filtering, we then employ a snowballing approach to also include papers from outside the ACM database.

Table 1: Literature search strategy

Categories	Boolean search string
Prototype	(Prototyp*) OR (object) OR (artefact) OR (artifact) OR (prototyping process) OR (prototype critique) OR (physical prototype)
AND	
Collaboration	(Collaborative design) OR (remote collaborative design) OR (distributed collaborative design) OR (cooperative design) OR (remote collaboration)

To accommodate the snowballing effort, we used the CONNECTED PAPERS [17].

3.2 Inclusion & exclusion criteria

We proposed four design strategies in the former tailored review (see background). During the paper selection process, we used them as our inclusion criteria.

Inclusion criteria:

- Improving the prototyping process (S1)
- Making bodily actions visible (S2)
- Providing different use of spaces (S3)
- Encouraging creative social practices (S4)

Exclusion criteria:

Collaboration methods, workflows, and frameworks were excluded from the selections since they often did not aim at supporting the prototyping process in actual design practices, but rather supporting remote communication in general.

3.3 Paper selection process

The selection process followed the steps outlined in the PRISMA guideline [64], as shown in Figure 1. Through ACM databases, 813 results were identified using search strategies. Following the screening process, we read the entire texts of 104 papers. To broaden our search fields, we used a snowballing approach to extend our search fields and find further relevant literature. Based on the papers that we already found, 34 additional papers were included in the assessment for eligibility. During our final selection, we tried to avoid

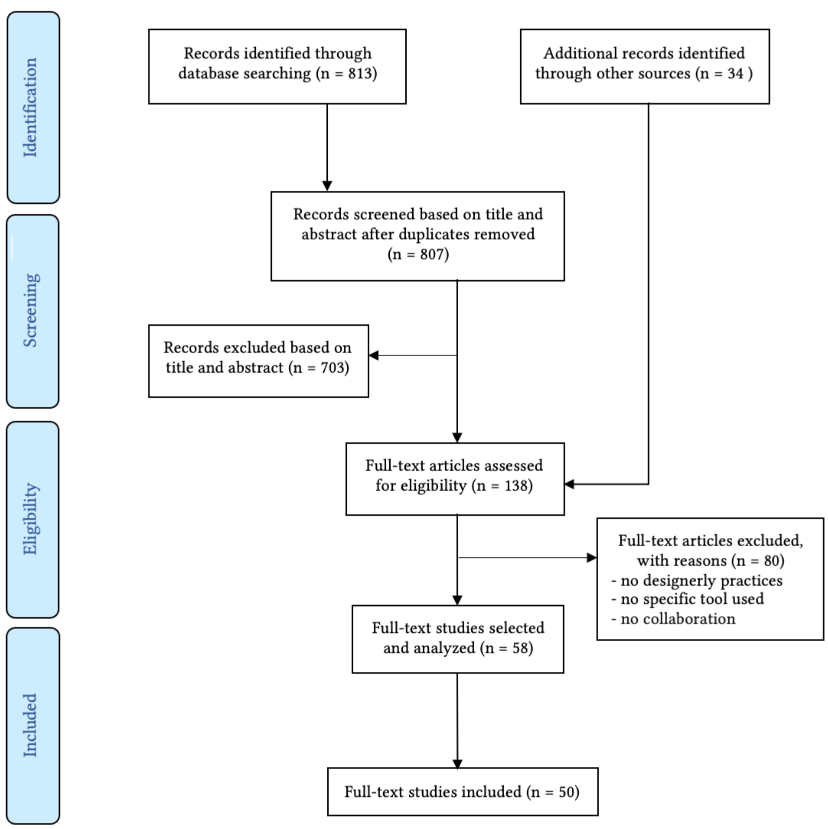

Figure 1: PRISMA flow chart of study selection process

Table 2: Overview of all 50 reviewed papers in different years and publications.

Years/Publications	CHI	UIST	IEEE International Symposium on Mixed and Augmented Reality	IEEE Transactions on Visualization and Computer Graphics	Journal on Multimodal User Interfaces	C&C	Others (TEI, DIS, CSCW, etc.)	Total
2013	[83]					[81, 100]	[35, 39]	5
2014	[66]		[47]				[1, 43]	4
2015	[3, 44]	[98]					[97]	4
2016	[24, 72]	[48]		[32, 40]			[28, 73]	7
2017		[57]			[36]		[14, 55]	4
2018	[4, 25, 70, 71]	[99]	[56]				[37, 61]	8
2019	[29, 46, 54, 88]	[52]					[10, 58, 74, 96]	9
2020	[6, 13, 59, 84, 104]				[45]			6
2021	[16]						[23, 34]	3

repeating similar supporting tools that used same technology and design method in slightly different contexts. However, for highly repetitive design cases, we kept two to three of them to compare the detailed design options. Some research papers are about a series of progressive but the same type of tools, so we chose the most comprehensive one. In this way, we enrich the selection but avoid repetition since this study aims to provide structured supporting strategies instead of investigating the development history of the collaborative design process. Eventually, eight papers were filtered out during the screening process. This review included 50 papers after the title and abstract screening, full-text analyzing, and rolling back to relevant studies in the reference of selected papers.

4 RESULTS

We included 50 papers from different venues in total. 20 papers were from CHI Conference (one of the top international conferences for the field of Human-Computer Interaction). Next to it, 5 papers were from UIST (User Interface Software and Technology), 2 from each of IEEE International Symposium on Mixed and Augmented Reality, IEEE Transactions on Visualization and Computer Graphics, Journal on Multimodal User Interfaces, C&C (Creativity & Cognition), and 1 from each of the venues of several others, for instance, TEI, DIS, CSCW, etc.

4.1 The gap between individual prototyping process and remote collaboration

As shown in Figure 2, we identified these 50 papers with two main categories: design and remote collaboration. Our standard for defining the included papers was whether the participants participated in design activities and had designerly practices. If so, we grouped them as 'design', and if not, as 'remote collaboration'.

29 of the 50 included studies focused on design processes related to the prototyping phase, and 24 on facilitating remote collaborative physical tasks. Four papers intersected these two fields. In these 29 design-related papers, 20 investigated supporting individual prototyping process, 9 papers targeted supporting collaborative design teams. Four of these nine papers explicitly targeted supporting remote collaborative design teams, three supported co-located design teams, and two were applicable to both.

25 papers focused on supporting remote collaborative physical tasks. From 17 out of 25 papers, physical tasks mainly referred to remote assembly, searching guidance, artefacts manipulation,

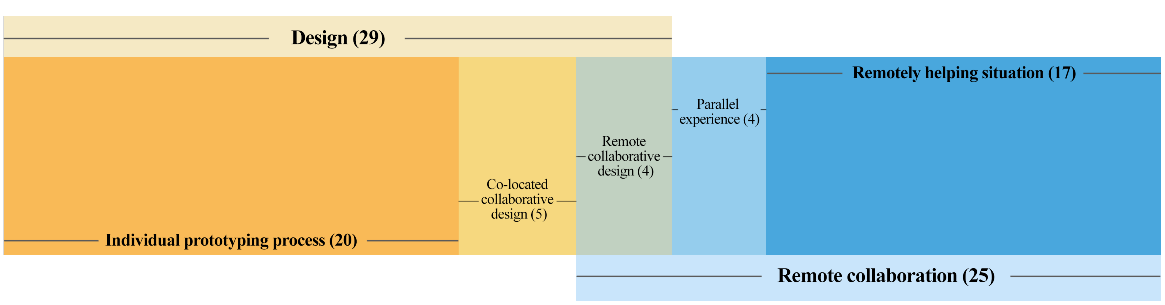

Figure 2: Different categories with numbers of the research

Figure 3: Distribution of 50 included papers in supporting strategies (S1: Improving the prototyping process. S2: Making bodily actions visible. S3: Providing different use of spaces. S4: Encouraging creative social practices)

etc. Kim et al. identified this type of collaboration as in a remotely helping situation [44], where the remote user is an expert helping or guiding the local user. Four papers out of these 25 focused on supporting parallel experience, in which “both users actively collaborate to achieve a goal and share the experience equally” [44].

4.2 Leading strategies for different domains

As we explained in ‘method’, we used four strategies as the selection criteria for understanding the present supporting tools. 20 of the 50 studies focused on assisting the individual prototyping process, 30 papers facilitated team activities. As depicted in Figure 3, we found that ‘*improving the prototyping process’ (S1)* was employed in every study as the foundation of the tool for supporting the individual prototyping process. For supporting group activities, however, ‘*encouraging creative social practices’ (S4) was* rarely used as a standalone strategy, instead, most selected papers used this strategy together with *‘making bodily actions visible’ (S2).*

Four papers [13, 39, 70, 73] used *‘providing different use of spaces’ (S3)* together with ‘*improving the prototyping process’ (S1)* to provide designers with a digital-physical mixed platform to explore their prototypes. The researchers exploited the strengths of digitalizing 3D prototypes to facilitate designers trying out different design concepts, making video prototypes and tracing histories of different design stages. Two papers [48, 59] employed *‘making bodily actions visible’ (S2)* during the prototyping process so that the designers could quickly create and easily adjust their interaction ideas.

Of the 30 papers for supporting team collaboration, only one paper [16] used *‘encouraging creative social practices’ (S4)* independently for improving video communication by providing more user-designed icons. The most commonly used strategies were S2+S4 (19 papers), followed by the combination with S3+S4 (5 papers) and S1+S3+S4 (3 papers). Two other papers based their tools on, respectively, S1+S2+S4 [83] and S2+S3+S4 [52].

4.3 Activities with varying degrees of complexity

As shown in Table 3, several different types of activities for demonstrating and evaluating the supporting tools were presented in the included 50 papers. We grouped these activities into three categories. Despite the actual design activities during the design process, we also defined two additional categories: simple object manipulation and complex tasks. Our judging principle was whether the participants were required to make a plan for achieving the goal. To be specific, finding and moving a Lego block by guidance is simple [32], whereas finding a way by discussion to assemble Lego blocks into a pre-defined shape is complex [37]. Note that all these activities were not limited to design activities only. We considered tools that support different activities during the prototyping process as being in the same spirit as utilizing general CSCW tools to support the collaborative design processes. Examples include pointing and assembling objects, measuring, and modifying prototypes, or communicating through hand gestures and other body languages, etc.

Simple object manipulation Researchers used some simple physical tasks to demonstrate the feasibilities of the supporting tools for remote collaboration. The most common three tasks were Lego assembling, making Tangram, and folding origami. Nearly 1/3 of the tools chose to use Lego for the activities in their studies [6, 14, 24, 28, 32, 35–37, 43, 45, 46, 56, 83, 88]. Typically, one collaborator guided the other collaborator in locating the correct pieces and then constructing a specific structure [1, 3, 10, 25, 55, 88]. Throughout the tasks, the collaborators had verbal communication with the assistance of different types of visual communication cues. For instance, eye gaze, sketches, pointers, or hand gestures. During the studies, the investigators normally did a set of comparing studies to evaluate different cues and their combinations.

Design process Since our searching keywords already set the scope of prototype-related design process, 25 of 29 tools focused on supporting the exploration process, while the remaining four papers [16, 61, 74, 81] provided some general support for design collaboration. Seven studies explicitly investigated the ideation phase [4, 29, 48, 54, 59, 70, 73]. For instance, Piya et al. [73] developed an interactive platform that allowed users to (a) scan and rearrange physical objects as modelling components, (b) modify the components to explore different forms, and (c) compose them into a meaningful 3D model. Other six papers focused on making prototypes [13, 39, 66, 83, 99, 104]. The difference between ‘explore’ and ‘explore (prototype only)’ was whether the tools could be immediately modified during the iterative prototyping process. We found 11 advanced tools for exploration. The following are two examples: the first one is SPATA developed by Weichel et al. [97]. SPATA contains two prototyping tools (a set of callipers and a protractor) that could bi-directionally transfer a measurement between the physical and virtual worlds; the second one was Roma from Peng et al. [71]. It is a prototyping system that provides a hands-on,

Table 3: Types and examples of included practices in the studies

	Practices	Studies	Description of a typical practice
Simple object manipulation	Lego: search, manipulation, assembly	[6, 14, 24, 28, 32, 35–37, 43, 45, 46, 56, 83, 88]	One collaborator is tasked to aid another collaborator in searching for specific Lego bricks and constructing a pre-defined shape.
	Simple objects: search, spatial arrangement	[1, 3, 10, 25, 55, 88]	One collaborator is tasked with guiding the remote collaborator to identify the needed blocks and then placing them into the right positions and orientations.
	Tangram Origami	[24, 44–47] [24, 45, 46]	Two individuals collaborate to solve puzzles or fold shapes while they are located in separate rooms. One places the pieces or folds the paper to match the shape that is shown on the reference paper held by the other.
Design process	Design process: explore (ideation only)	[4, 29, 48, 54, 59, 70, 73]	The user captures 3D spatial information and positions the 3D objects in situ, combining 2D drawings with 3D objects in a virtual environment.
	Design process: explore (prototype only)	[13, 39, 66, 83, 99, 104]	Designers interact with 3D objects in two ways: 1) by putting them in a virtual world and changing their position, scale, and orientation; and/or 2) by using "smart materials" that synchronize their virtual shapes as they are changed in the real world.
	Design process: Explore (ideation and prototype)	[23, 34, 40, 57, 58, 71, 72, 84, 97, 98, 100]	Designers modify the prototypes more efficiently because the tools 1) synchronize the prototypes between physical and virtual worlds; and 2) allow them to quickly interrupt the printing process so that they can adjust the prototype as they want.
	General support for design collaboration	[16, 61, 74, 81]	Designers provide rich information during video-mediated communication. For instance, icons of their reactions, audio/video annotated with reflections, and/or fully documented and traceable design process.
Complex tasks	Others: repair task, real assembly case, teaching	[37, 52, 96]	The users collaborate remotely on various real-world activities. Their tasks include repairing a computing device, assembling a water pump, or instructing in guitar, sculpting, or baseball.

in-situ prototyping experience where design and making are closely intertwined.

Complex tasks We found three papers in this category. Complex tasks, which differ from simple object manipulation, are normally closer to real-world activities. During the study, users were given a goal and required to decompose it into several steps. To provide a clearer view, we present an example of Loki, designed by Kumaravel et al. [52]. Loki provides a real-time rendering of the user's relative position to where they observed the other collaborator. This tool uses bi-directional, mixed-reality telepresence technology to facilitate online instruction of guitar playing, sculpture, and baseball training. In addition, we also encountered a few additional simpler complex tasks, such as remotely guiding the assembly of an actual water pump [96], simulated repair task [37].

4.4 Heavy usage of predetermined roles

Thirty papers studied co-located or remote collaboration, comprising design and physical tasks. Table 4 depicts the distribution of 30 papers in different combinations of roles and their corresponding types of collaboration. We found that in studies focusing on supporting users in remote help situations, the roles of the participants were frequently predetermined. For instance, they referred to one of the participants as remote expert [1, 3, 6, 45, 46, 96], remote helper [14, 24, 28, 32, 35–37, 55], ghost

Table 4: Distribution of 30 papers in different combinations of roles and their corresponding types of collaboration.

Roles of collaboration	Remotely helping situation	Parallel experience	Design
Remote expert* + Local novice**	[1, 3, 6, 14, 24, 25, 28, 29, 32, 35–37, 43, 45, 46, 52, 55, 56, 88, 96]	[46, 52]	[25]
Remote user + Local user	[10, 44, 47, 83]	[44, 47]	[29, 83]
Collaborative design team			[16, 58, 61, 74, 81, 84]

(*Expert referred to as ghost, helper, instructor, etc. in the studies; **Novice referred to as body, worker, learner, etc. in the studies)

[43], while they referred to the other participant as local novice [3], local worker [1, 6, 14, 24, 28, 32, 36, 45, 55, 96], body [43] (see table 4). From the predefined names, we could get a glimpse of what the participants were expected to do during the experiments. The remote expert would contribute their expertise and act as a guide for the person they work with on the other side, while the local novice would encounter problems and has no idea what to do. When we looked at the other papers which contributed to 'parallel experience' and 'design', we found that the participants were seen as equals or as a team that always cooperated with each other. Six out of nine design-related research papers, for instance, referred to their participants as a collaborative design team.

4.5 Differences between the use of technologies depending on the roles

Thirty papers investigated supporting team activities. As illustrated in Figure 4, we analyzed 24 papers to determine how technologies have been used on both sides to support remote collaboration. We counted the number of different combinations of technology. Larger values were represented by dark blue and smaller values by lighter blue. For the following reasons, six papers did not apply to the two dimensions:

Four tools [16, 61, 74, 81] were developed based on digital software that focus on non-design-oriented support.

Two papers [58, 84] were excluded from the map since they only support co-located design collaboration.

Compared to the two dimensions of this heatmap, augmented reality (AR), virtual reality (VR), AR/VR, and video appear on both sides. Nonetheless, combinations employing the same technology on both sides are uncommon. Sixteen studies presented the extensive use of AR on the local side: among these 16 papers, 7 studies showed that remote users were using VR to see the local users' environment, while the other 8 studies demonstrated that remote users could also use videos to perceive more information; One study [83] used AR on both sides for mobile collaborative 3D interactions. AR/VR is a rare case because it exists only when both sides have the same settings: Loki [52] provided the users with both AR and VR modes during the remote collaboration so that they could alter their views and perspectives independently. Video appears to be a useful technology for both parties. In addition to observing what other users are doing, videos can be used to exchange information. For instance, AlphaRead [14] introduced readable object annotations overlaid on the videos to support unambiguous remote communication referencing. Sensors and robot arm is also a combination for supporting remote collaboration. To ensure that the remote user shared the same views and perspectives as the local user, ReMa [25] provided a system that cooperated with a robotic arm capable of reproducing orientation adjustments on a proxy object at the remote site. On the local side, a projector was used twice with video [1] and VR [96], respectively.

4.6 Three commonly used visual communication cues

In co-located face-to-face collaboration, various communication cues are used. For example, audio (e.g., speech, paralinguistic, intonation), visual (e.g., gaze, gesture, facial expression, body posture), and environmental information (e.g., object manipulation, writing, drawing, spatial layout) [6]. In their studies on remote collaboration, researchers examined three visual communication cues in their studies: pointers, gestures, and annotations/sketches. They undertook a series of comparative studies to evaluate several factors, such as working efficiency, the feeling of co-presence, the mental effort required, etc. Nine papers employed a pointer to represent their finger-pointing or their eye gazing, 22 papers supported users in showing their hand gestures or even body gestures, 19 papers allowed users to make annotations and sketches overlaid on the images of the objects.

5 DISCUSSION

The main objective of this literature review was to provide an overview of the design space for supportive tools for the remote collaborative design process. This concerns the ways in which designers collaborated, the functions provided by these tools, the practices in which designers participated, and the ways in which these tools were evaluated.

5.1 Focus on mechanisms to support remote co-exploration

As shown in Figure 2, fifty papers were divided into two main categories: design and remote collaboration. We noticed that the current tools from these two categories employed two independent mechanisms with only a few tools applying both. The first mechanism refers to individual design or prototyping processes that require tools to build bridges between digital and physical prototypes, while the second mechanism refers to remote collaboration situations involving physical tasks that have no design or prototyping context.

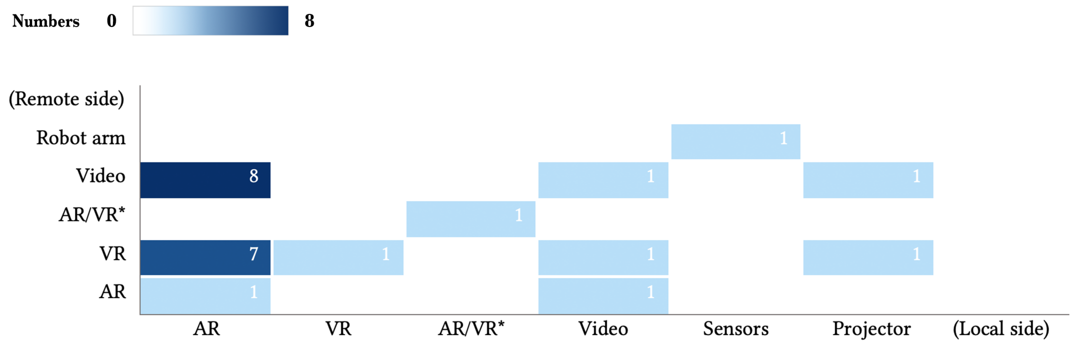

Figure 4: Heatmap of different types of technology in 24 tools for remote collaboration (AR/VR*: users could switch these two modes individually according to their needs during the tasks)

Table 5: Visual communication cues of included tools

Visual communication cues	Studies
Pointer	[6, 10, 13, 24, 32, 43, 46, 47, 88]
Gestures	[3, 6, 10, 28, 29, 32, 35–37, 45, 46, 48, 52, 55, 56, 58, 59, 73, 83, 84, 88, 96]
Annotations/ sketches	[13, 14, 24, 29, 32, 37, 44–47, 52, 55, 58, 61, 84, 88, 96, 98, 99]

It is conceivable that the first mechanism where digital or physical tools are proposed for bridging digital and physical prototypes can be employed to support remote collaboration. It is crucial to see that this cannot be a direct translation of the tool but that these tools need to be re-designed for remote collaboration. The tools would need to be designed such that parallel exploration is supported in a way that is informed by how designers explore when physically co-located.

The objective of remote collaboration tools outside of the context of design or prototyping was to bring two parties into a virtual world. As indicated in Table 4, 20 out of 30 studies focused on supporting users in one-directional 'helping' scenarios. This 'puppeteer' situation, in which one collaborator (the physical collaborator) is directed by the other collaborator (the digital collaborator), is not typical of normal designerly co-exploration.

We advocate an improved working scenario that should not be approached as one user helping another, but rather as a shared parallel experience, in which both collaborators are fully engaged in the shared activities. In section 4.3, we introduced Loki [52] while discussing the different activities in the studies. Loki takes a big step further by providing a real-time bi-directional interface that allows collaborators to switch between each other's environments. In a similar vein, we believe that future projects should pay more attention to both of these two bi-directional mechanisms to support remote design co-exploration.

5.2 Increase opportunities for co-exploration

As shown in Figure 4, we generated a heatmap depicting the various types of technologies employed in selected tools for supporting remote collaboration. We continue to refer to these two parties as 'local' and 'remote' because most of the tools were tested in one-directional 'helping' situations. The local party used a wider range of technologies than the remote party. On the local side, AR and VR were the most popular technologies, followed by Video on the PC or tablet, and projecting on top of the workspace. On the other hand, users from the remote party heavily rely on videos and VR.

We argue that the predefined roles determined which technologies were used, resulting in an unequal environment for co-exploration. We investigated further to see the tasks of the experiments. The local party was required to 1) record what they intended to discuss with the other and mostly ask questions about the next actions, and 2) receive the answers from the remote side. While the remote party was asked to 1) understand the information provided by the local side, and 2) record and transfer their comments such as verbal explanations, gestures, sketches, annotations, etc. The tools they used, and their perspective of vision were determined by their predefined roles. The local party had an independent perspective of vision. They are free to move around and use one or more cameras to record items they want to share. The remote party, in contrast, could only have a dependent perspective of vision. Because they were designed to be an information provider with no need to share their working environments or ask any further questions.

However, this working scenario described a typical remote collaboration on physical tasks that cannot be simply copied to the remote collaborative design processes. This one-directional helping situation limits the ways in which designers collaborate with each other. As we mentioned before, it also constrained designers from sharing a parallel experience. In future studies, we think that it is necessary to emphasize that users should make the call about which technologies to utilize. The supporting tools should provide both designers with the same opportunity for exploration.

5.3 Understand the needs of co-exploring designers

We identified four design strategies from previous work and used them as our selection criteria. Figure 3 depicts the distribution of 50 included papers in supporting strategies section (S1: Improving the prototyping process. S2: Making bodily actions visible. S3: Providing different use of spaces. S4: Encouraging creative social practices).

We noticed that it was rare to find examples of supporting the co-exploration processes in a distributed environment. Most of the present tools were geared toward supporting either the individual prototyping process or team collaboration on simple physical tasks. For supporting the prototyping process on one party's side, we found that the core was accelerating the prototyping process and synchronizing the physical and digital prototypes. For supporting team collaboration on physical tasks, making bodily actions visible to the other party was the vital function of the tools.

The distribution of design strategies for supporting remote design collaboration prompted us to find an underexplored opportunity: whether we should seek the integration of all design strategies into a single tool, or shift our way of thinking to find the most efficient strategies during different design phases and thus build them into a supporting system. For bi-directional remote design collaboration, we argue it is important to establish a platform that provides both parties access to both the person and the materials. Meanwhile, we propose that we should examine the designers' needs of each remote collaborative design phase. These phases include, for instance, the phase in which designers want to be updated on design outcomes, the phase in which designers need to check back and forth on the making processes, and the phase in which designers are willing to co-make and co-explore.

In addition, we found only little research focusing on supporting remote design collaboration that included the prototyping process. We identified four design strategies based on the insights from improving co-located design collaboration. We argue that only mimicking co-located collaborative design processes might not be sufficient to support remote design collaboration. For example: when the pandemic lockdown began, there was a significant shift to online meetings. Microsoft Teams provided a "together mode" trying to make people feel more engaged even while they were working at various locations. Together mode maps everyone's video stream onto one shared virtual background, creating the illusion that everyone is in the same room. This feature was widely used at the beginning, and it was entertaining and pleasant to see people in the meeting room anyway. However, people eventually realized that it was inconvenient to not be able to see who is speaking, and presenting items, or sharing screens. Digital meetings have different requirements than physical meetings, thus mimicking the real meeting situation is not as practical as we thought at the beginning. It reminds us to keep conscious of the possibility that remote collaboration will have different needs and thus have different design tools or even design processes as more conventional co-located collaboration. Our four design strategies should serve as a starting point for future research. We should also examine if they are applicable to remote design collaboration in the same manner, and if designers' needs change in remote collaboration contexts.

5.4 Consider a comprehensive set of design practices.

In the background section, we presented experiments that indicate different impacts of remote design collaboration. We argued that next to studying the ideation phase (e.g., sketching and brainstorming), the exploration phase (e.g., iterative prototyping process) also needs to be studied. We can observe from Table 3 that there is still a gap between simple object manipulation, and design exploration. Folding origami, solving tangram puzzles, or assembling Lego concerns more making and discussing than creating. Current evaluation regarding remote collaboration often uses communication efficiency, user satisfaction, language use, and the sense of co-presence to compare the benefits of the tools. To examine the supporting tools for co-exploration during remote design collaboration, we should consider using more design-related frameworks or structures for checking different aspects. This is in line with other comparative studies between co-located and remote design collaboration, the function-behavior-structure (FBS) [12, 86] and information-problem-solution (IPS) [102] were utilized as coding approaches to evaluate the supporting tools. Thus, our future studies should consider conducting more structure-based design practices in the studies related to functional arrangement, interaction behavior, or structure changing problems.

5.5 Limitations

In our review we encountered a large number of papers addressing the topics of brainstorming, sketching, project management, and reflection. We identified these topics as potentially interesting but out of scope for this literature review.

In a similar vein, we searched for concrete design and collaboration tools, hence collaboration methods, workflows, and frameworks were also not included in the final set of papers.

We have flagged these additional topics for further exploration and for use by other researchers.

6 CONCLUSION

The purpose of this review was to present an overview of the design space for improving the remote collaborative design process. We investigated papers published between 2013 and 2021 in the ACM Digital library. 50 papers were included following the PRISMA process. As introduced, we see the co-exploration process as an important phase that has remained underexplored. We analyzed the selected papers from multiple angles, including the ways in which designers collaborated, the functions provided by these tools, the practices in which designers participated, and the ways in which these tools were evaluated. Our work identified gaps and opportunities for future research and tool development in the remote collaborative design process.

For future research, we sketch out our research agenda consisting of three topics: 1) designing tools for supporting co-exploration throughout the remote collaborative design processes, 2) extending the research studies involving more phases of shared experiences, 3) considering conducting more structure-based design experiments and applying more design-related evaluation criteria. Explanations of each topic are as follows:

First, we found that there were relatively few studies claimed to support the remote co-exploration process. Current tools have mostly explored two related fields: individual prototyping process and remote collaboration on physical tasks. Arguably, when we improve each party's prototyping process or share more bodily actions, there is a good chance that remote co-exploration will be enhanced. However, little research has been conducted on the technologies that support co-exploration during the remote collaborative design processes. Therefore, our first step is to use the knowledge we've gathered to develop a comprehensive understanding of the designers' needs in different phases during the remote collaborative design process. Based on this, we can further evaluate the effects of different supporting design strategies.

Second, unlike designers who work co-located, remote collaborators employed various technologies for sharing what they see and how they act. However, current studies often set the context of collaboration as a one-directional helping situation. Researchers therefore predefined the technologies. That resulted in one collaborator's vision perspective being frequently dependent on the other. In future studies, we plan to more closely simulate the actual collaboration context, i.e., both parties actively collaborate to achieve a goal and share the experience equally ('parallel experience'). Regarding the technologies, we think that the participants should be able to decide from which perspective of vision to see and which suitable technology to utilize.

Finally, researchers often evaluate the communication efficiency, user satisfaction, completion time, and other factors to assess the efficacy of supporting tools for remote collaboration. However, there is still a gap between the tasks in the studies and the actual design process. We argue that additional design-related aspects, such as the depth and breadth of the discussion of a design, the level of creativity and reflection, and design output, must also be examined. Our future research needs to consider conducting more structure-based design practices and evaluating more design-related elements.

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