A Survey of Computer-Supported Remote Collaboration on Physical Objects

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Abstract. The need for remote collaborative work is constantly increasing. Collaboratively adapting digital content, such as documents and images, has come to a stage where it is part of our daily lives. In comparison, remote collaboration on *physical* objects has matured at a slower pace, even though this is a possible step towards location-independent cooperation and therefore equality in work. In this paper, we present a structured literature review on computer-supported remote collaboration on physical objects from the last 23 years. Our contribution is threefold: First, we provide a comprehensive analysis of the current state of research on the topic of remote collaboration on physical objects. Second, we identify multiple research gaps, such as inclusion of haptic sense, mutual collaboration, and asynchronous collaboration. Third, we analyze code relationships in the selected publications and provide directions for future work in the form of exploratory research questions.

Keywords: Literature Review · Remote Collaboration · Physical Objects

1 Introduction & Background

Traditionally, collaborative work on physical objects is done by people in the same place at the same time. As companies are increasingly dependent on a global workforce, remote teams are becoming the norm. Currently, there are two ways to support remote teams that are working on physical objects: (1) They can either travel to each other, which results in high monetary and environmental costs [55]. Additionally, employees are strained by off-rhythm work schedules and jet lag [62, 19]. (2) Alternatively, they can make use of collaborative tools for working remotely. For example, by prototyping with virtual abstractions of physical objects on 2D screens such as Figma [22] or 3D modeling in the form of Computer Aided Design (CAD) software, for example AutoCAD [7], Solidworks [18], or Blender [23]. While these approaches have the benefit of enabling remote collaboration through a fully digital workflow and allow for accurate fabrication, they detach the physical object from the physical world.

We see numerous reasons for emphasizing *physical* objects and reviewing research in this area to date. First, the naturalness of interaction that drives people to work with physical content, despite the advantages of digital workflows. An example for this is the creative domain, such as arts, product design, and craftsmanship, in which traditional painting as well as sculpturing are common practices despite the existence of drawing programs and 3D modeling tools [54]. The second reason is that our everyday lives are first and foremost rooted in the physical reality. Regardless of how digitization will shape the nature of productive work, the world we live in is physical and our daily needs will be physical and then only virtual. To this date, physical objects are by nature bound to space and therefore strongly limited in flexibility, compared to virtual objects that allow for replication, modification, and instant transfer. However, as novel technologies, like Augmented Reality (AR) and Mixed Reality (MR), grow more mature, new possibilities for collaborating on physical objects arise. These developments have the potential to overcome the fundamental disconnection between the physical world and digital information [81], thereby enabling better cooperation on physical objects independent of location, increasing equality in work.

In the context of this paper, the term *physical object* refers to content that is part of the real world and can be either a single artifact or an environment. We further specify physical objects as three-dimensional to exclude quasi two-dimensional artifacts like printed text documents or images. Since co-located work on physical artifacts most times does not require technical support, our work only examines remote collaboration.

A plethora of reviews has been conducted that touch on collaboration with physical objects [67, 60, 59, 10, 9, 95, 87, 53, 79]. Contrary to prior work, we present a structured literature review that amalgamates technology-focused surveys *and* Computer-Supported Cooperative Work (CSCW) literature, focusing on the current state and possibilities of remote collaboration on physical objects, rather than on the sole use of a technology or the social properties of a collaboration. In the following, we provide an overview of prior work to highlight specific gaps that we aim to fill with our structured literature review.

In 2018, Limbu et al. conducted a Structured Literature Review (SLR) of publications between 2014 and 2016 on AR for training [59]. They concluded with a promising outlook towards the development of AR and sensor technology. As a research gap, the use of sensors for capturing cognitive aspects of expert performance was identified. Opposed to the work of Limbu et al., we aim to investigate all possible collaboration scenarios and technologies, while scoping to works that actually include physical objects.

A systematic review on collaborative MR technologies was done in 2019 by Belen et al., including publications from 2013 to 2018 [10]. In their conclusion, Belen et al. pointed to potential research gaps in systems that support both co-located and remote collaboration, as well as in asynchronous collaboration. The work was limited to MR technologies and did not highlight the role of physical objects as the subject of collaboration.

In their work from 2020, Wang et al. provided a comprehensive survey of AR/MR-based co-design in manufacturing [95]. Analyzing publications from 1990 to 2017, they assessed the suitability and benefits of AR/MR environments for co-design. Their selected literature regarded manufacturing purposes and included co-located and remote interactions. While the use of AR has physical aspects by design, the examined applications rather utilized virtual object representations, similar to CAD programs. The authors concluded with the potential to establish an empathic co-design system and suggested the integration of AR/MR in commonly used CAD programs. In our approach, we elaborate on the role of physical objects and the activities that form around them in remote setups. The examined spectrum of application areas in our survey is not limited to manufacturing and technology-open.

Lapointe et al. reviewed the literature on AR-based remote guidance tasks in their work from 2020 [53]. They concluded with AR-based remote guidance being usable in variable application areas. As the scope of the survey was on the scenario of a remote expert helper guiding a local novice worker, other collaboration scenarios were not regarded. We aim to address this aspect of remote collaboration while including scenarios that go beyond guidance, as well as reviewing all available technologies.

In year 2020, Pidel and Ackermann presented a systematic overview on the collaboration in Virtual Reality (VR) and AR [79]. As a main finding, the underrepresentation of asynchronous collaboration was named. Our approach focuses more on the aspects of remote collaborations that form around physical objects, while Pidel and Ackermann provided a more general overview, as their research objective were not physical tasks.

Schäfer et al. conducted a survey on synchronous AR, VR, and MR remote collaboration systems in 2021 [87]. While some selected publications overlap with our selection, the work by Schäfer et al. mostly examined purely virtual content, such as meetings and digital design. The authors concluded with audiovisual systems being the default setup and guidance scenarios being the main use case for AR and MR, while in comparison, VR is more often suitable for equal involvement of collaborators. In comparison, our survey is technology-open but requires the collaboration to evolve around a physical artifact. Also, our work includes all collaboration types, including asynchronous collaboration.

Furthermore, numerous literature reviews have been published that investigate either related technologies [75, 63, 12] or collaboration aspects [60, 52, 99], without regarding the interaction between the two areas. Similarly, works of Hassenzahl et al. [32] and Li et al. [58] provide insights in the transfer of physicality across distance, but do not study the collaboration on physical objects.

The presented works show similarities in the collection of selected papers, as authors systematically searched through mostly same libraries (ACM DL [1], SpringerLink [5], IEEE Xplore [35] being used most often) using similar query keywords (collaboration, collaborative being used most often in combination with technologies like AR and MR). While there have been numerous literature reviews on computer-supported collaboration [95, 53, 87, 10, 79, 59], limited research has been done concentrating the collaboration on physical real-world objects. The related surveys presented either give a general overview on the collaboration in MR or AR [10, 79, 87] or target specific collaboration scenarios, namely co-design [95], guidance [53], and training [59]. To the best of our knowledge, there has not been a systematic review of literature on the remote collaboration on physical objects.

To fill the above-mentioned gaps in prior work, we conducted a SLR, which sets out to gain a deeper understanding of the current state of remote collaboration on physical objects. A SLR is a systematic approach for evaluating all available research to a topic of interest [48]. We make the following contributions:

(1) Comprehensive overview of the current state of research on the topic of remote collaboration on physical objects; (2) Identification of research gaps; (3) Analysis of code relationships and provision of exploratory research directions.

Our findings will help scientists that plan to participate in research on remote collaboration on physical objects. Developers and researchers working in overlapping research areas will also find the results useful in understanding how their contributions may affect research on remote collaboration on physical objects.

2 Method

The goal of this SLR is to gain an overview of existing work that addresses computer-supported remote collaboration on physical objects. Similar to prior SLRs [60, 8, 69], we follow the guidelines defined by Kitchenham's work "Procedures for Performing Systematic Reviews" [48] as described in the following.

We formulate the research question for this survey as: "What aspects of remote collaboration on physical objects have been explored in scientific literature?". The research question will be answered by reviewing work in this field of research using an unbiased approach [48].

For the extraction of publications, the ACM digital library [1], SpringerLink [5], and IEEE Xplore [35] were selected as databases, since they are the databases used most frequently by related literature surveys as well as most relevant to HCI research. The query chosen for extraction of work was: *(cscw OR "computer supported collaborative work" OR "tele-collaboration" OR "distributed collaboration" OR "remote cooperation" OR "remote collaboration") AND ("physical task" OR "physical object" OR "tangible object" OR "physical artifact" OR "physical computing").*

The total of 1093 search results were composed of 317 results for the ACM digital library, 771 results for SpringerLink, and 5 results for IEEE Xplore. The search was performed in late 2020 and refreshed mid 2021. Of the 1093 entries, a filtering process reduced the amount to 80 publications in the end. A history of the selection process is presented in supplementary material.

The final iteration of our coding process overlapped with the release of the CHI program in 2021. To the best of our knowledge, this was the only conference program that was released at the time of coding - from the list of relevant conferences that we had already synthesized during earlier coding rounds. Due to the high confidence we had, at this point in the coding process, on what relevant conference venues were for our literature review, we decided to include the papers from the CHI conference that matched with our search query keywords. This resulted in the inclusion of 4 additional papers in the last coding stage.

A more comprehensive report of the search and filtering process, including explanation of filtering criteria, can be found in the supplementary material.

3 Results

Our results consist of a list of the codes/codebook that were created during an open coding process by two researchers. Their numbers of appearance can be found in table 1. The number of retrieved papers, broken down by publication date, is visualized in the top of figure 1, which shows a constant increase of works in that field. Codes that represent a category of codes and are indicated by an uppercase letter at the beginning, while in-text codes are written with a lowercase letter at the beginning.

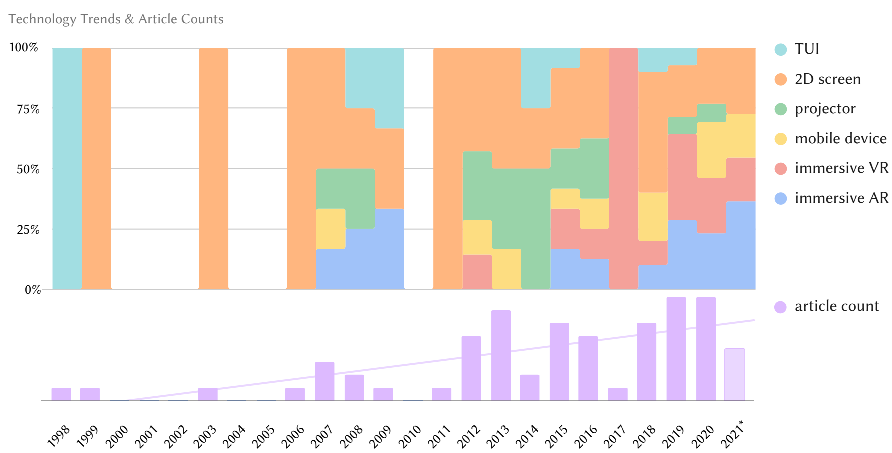

Fig. 1. Work on remote collaboration on physical objects by publication date. Top: Technologies in relation to the total amount of publications in a year, scaled to 100% for each year. The most common technologies and devices in the *Technology* code are selected. A trend towards technology diversification can be identified. Bottom: Amount of publications per year. An increasing amount of publications is visualized by a trendline. However, multiple increases and drops of publication numbers can be identified. 2021* only until June of the year, see section 2.

Application Area describes the field of application or professional domain which is considered or at least named as an exemplary use case by a publication. We differentiate between five fields of work: *health* (n=14); *scientific* (n=2); *industrial* (n=34); *educational* (n=10); and *entertainment* (n=6). It should be

Code	Count	Ratio
Research Focus		
physical object	8	10%
object interaction	8	10%
environment	8	10%
device setup	4	5%
concepts and theory	3	4%
User		
collaboration	15	19%
Viewpoint		
viewpoint control	7	9%
viewpoint independence	4	5%
shared perspective	4	5%
Communication		
annotations	6	8%
gestures	16	20%
gaze	6	8%
Application Area		
industrial	34	42%
entertainment	6	8%
educational	10	12%
health	14	18%
scientific	2	2%
Study Design		
Study		
field study	2	2%
lab study	61	76%
Data Types		
task performance	39	49%
behavioral measure	18	22%
perceptual measure	31	39%
presence	11	14%
workload	8	10%
Method		
questionnaire	42	52%
interview	27	34%
conversation record	31	39%
quantitative tracking	15	19%
heuristics	14	18%
Task		
assembly	36	45%
placement	12	15%
operation	9	11%
repair	7	9%
search	10	12%
playing	5	6%
design	5	6%
functionality test	8	10%
Materials		
dummy material	46	58%
realistic material	27	34%
continuous material	2	2%
Recommendations		
design recommendation	46	58%
research recommendation	10	12%
hardware recommendation	7	9%
methodology recommendation	3	4%

Code	Count	Ratio
Prototype Setup		
symmetric system	22	28%
asymmetric system	60	75%
static	39	49%
portable	41	51%
large scale	29	36%
small scale	50	62%
Collaboration Type		
mutual	17	21%
training	3	4%
guidance	62	78%
synchronous	79	99%
asynchronous	6	8%
dyadic	79	99%
multiuser	1	1%
Targeted Senses		
auditory (only)	5	6%
auditory + visual	71	89%
auditory + visual + haptics	9	11%
Technologies		
2D screen	55	69%
projector	21	26%
2D video	52	65%
monocular camera	47	59%
depth camera	19	24%
SLAM	3	4%
photogammetry	1	1%
RFID	2	2%
360 degrees video	4	5%
mobile device	19	24%
spatial AR	9	11%
immersive AR	19	24%
immersive VR	17	21%
mobile device AR	4	5%
tabletop	3	4%
TUI	8	10%
robotic device	7	9%
rapid prototyping	2	3%
head-up display	5	6%
LED Lights	3	4%
actuators	3	4%
shutter glasses	1	1%
machine learning	1	1%
Tracking		
2D-marker-based	9	11%
marker-less	2	2%
hand / fingers	10	12%
head	10	12%
eye gaze	7	9%
object	8	10%
Input Devices		
mouse + keyboard	13	16%
touchscreen	11	14%
pen	7	9%
glove	3	4%
controller	6	8%

Table 1. Codebook. The 94 codes, their total number of appearances, and appearance ratio in comparison to the total amount of works (total 80 works, ratio rounded to 2 digits). Codes in bold represent parent codes that were added to categorize results.

noted, that many of the studied works do not specify any *Application Area*, while others name several. We did not code an *Application Area* for works that might be associated with a field of application when it is never named.

Research Focus describes the main topic the work investigates. Publications are usually coded with a single *Research Focus*, in some cases with two. Notably, each of the selected works explores remote collaboration on physical objects, even if the research focus is not on the object itself. We differentiate between six different focus topics: *physical object* (n=8), *environment* (n=8), *object interaction* (n=8), *device setup* (n=4), *concepts and theory* (n=3), and *User* (n=58). Because of the high amount of *User*-focused works, we divided this code in multiple sub-codes. Besides a focus on *collaboration* (n=15) between users, we identified two larger fields that can be further differentiated: *Viewpoint* (n=15) and *Communication* (n=28). *Viewpoint* is divided into *viewpoint control* (n=7), *viewpoint independence* (n=4), and *shared perspective* (n=4). The code *Communication* has the sub-codes *gestures* (n=16), *annotations* (n=6), and *gaze* (n=6).

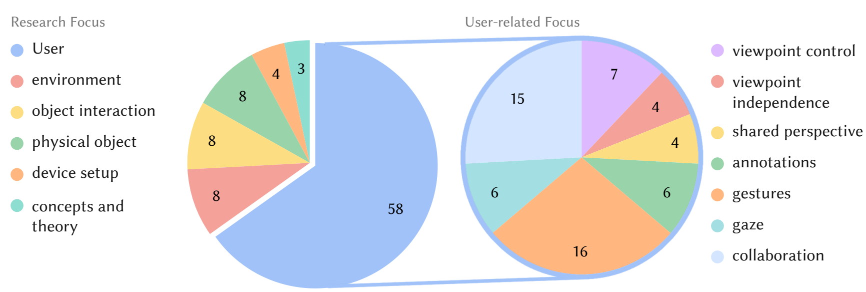

Fig. 2. Left: Comparison of *Research Focus* codes against each other, most works focus on *User*-related themes (divided by gap for clarity). Right: Distribution of sub-codes in the *User*-focus segment (total 58 works). Intermediate code layers regarding *User-Focus* are not visualized; *viewpoint control*, *viewpoint independence*, and *shared perspective* are categorized under the code *Viewpoint*; *annotations*, *free-form gestures*, *gestures pointing*, and *gaze pointing* belong to the parent code *Communication*.

Prototype Setup describes the properties of a proposed technical setup. We identify three properties that each can be separated into two states. The first property is the scale a prototype supports, divided into *small scale* (n=50) and *large scale* (n=29). If a prototype supports *large scale*, it can usually also be used in a *small scale* setup. The setup movement capabilities are further differentiated as *portable* (n=41) or *static* (n=39). If a prototype is *portable*, it can usually also be used in a static scenario. Lastly, we distinguish between *symmetric* (n=22) and *asymmetric* (n=60) systems, depending on how similar the systems in use are (in line with the definition by Heldal et al. for collaborative virtual environments [33]). In some cases, a prototype system can be used both in a *symmetric* and an *asymmetric* variant.

Collaboration Type describes the relationship between collaborators and how the collaboration takes place. The types of collaboration are coded as *training* (n=3), *guidance* (n=62), and *mutual* (n=17). As a reference, mutual collaboration is in line with how Feld and Weyers describe a symmetric environment, while guidance and training are collaborations in an asymmetric environment [21]. Furthermore, we differentiate between *synchronous* (n=79) and *asynchronous* (n=6) collaboration. A work can support both *synchronous* and *asynchronous* collaboration. Lastly, a publication can regard a *dyadic* (n=79) collaboration or a *multiuser* (n=1) scenario.

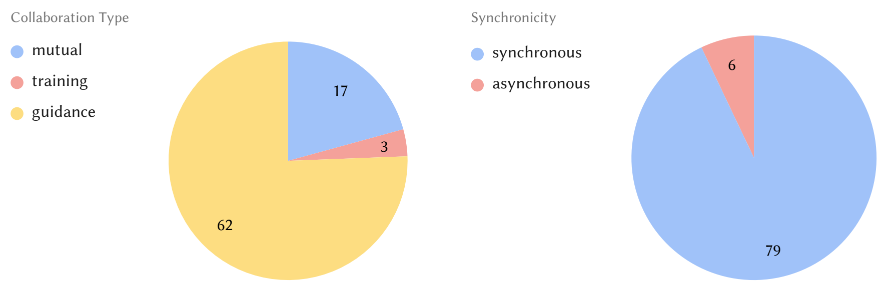

Fig. 3. Comparison of *Collaboration Type* codes against each other. Codes regarding the synchronicity are displayed separately. *Guidance* is the most often used type of collaboration, while *mutual* and *training* scenarios are rarer. Regarding the synchronicity of a collaboration, almost every work regards a *synchronous* but very rarely an *asynchronous* collaboration.

Technologies describe both hardware and software solutions that are used in a prototype and were observed throughout the reviewed works. While there is no need for further segregation, we sort the sub-codes in the order of input technologies, mixed technologies, and output technologies for convenience. For input technologies, we coded *monocular camera* (n=47), *depth camera* (n=19), and *RFID* (n=2). Besides, the following *Input Devices* were identified: *mouse + keyboard* (n=13), *touch screen* (n=11), *pen* (n=7), *glove* (n=3), and *controller* (n=6). One group of technologies processing the input content are *Tracking* technologies. *Tracking* is divided into *marker-based* (n=9); *marker-less* (n=2); *hand/fingers* (n=10); *head* (n=10); *eye gaze* (n=7); and the tracking of *objects* (n=8). As mixed technologies, that can serve as both, input and output, or have other processing uses, we identified the following codes: *2D video* (n=52), *360 degrees video* (n=4), *mobile device* (n=19), *mobile device AR* (n=4), *spatial AR* (n=9), *immersive AR* (n=19), *immersive VR* (n=17), *tabletop* (n=3), *tangible user interface* (n=8), *robotic device* (n=7), *SLAM* (n=3), *photogrammetry* (n=1), and *machine learning* (n=1). We point out that the codes *2D video* and *2D screen* correlate with the vast area of video-mediated collaboration, that is extensively studied in CSCW literature. The section of works analyzed in this SLR, that regard physical tasks or physical objects, is only a small part of video-mediated collaboration. As output technologies, we coded *2D screen* (n=55), *projector* (n=21), *head-up display* (n=5), *rapid prototyping* (n=2), *LED lights* (n=3), *actuators* (n=3), and *shutter glasses* (n=1).

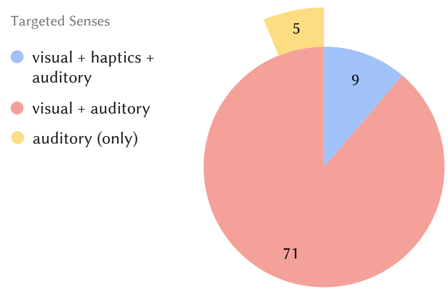

Fig. 4. Comparison of *Targeted Senses* codes against each other. The code *auditory (only)* is overlaid, as it is an optional condition, while the others combine to 80 as the total amount of papers. The majority of works utilize audio-visual solutions without regarding haptics.

Targeted Senses describe the senses that are addressed by the proposed prototype in a work. We differentiate between *auditory (only)* (n=5), *auditory + visual* (n=71), and *auditory + visual + haptics* (n=9). In every presented prototype application, at least the *auditory + visual* senses are targeted. The *auditory (only)* condition serves as a control condition, as there is no work in which the auditory sense alone is targeted, given to our inclusion criteria. The code *auditory (only)* was not given to works in which the input of one of the collaborators is only voice while observing their partner's actions, as this term is used in multiple works, e.g. [73, 47, 44]. A work coded as targeting the senses *auditory + visual + haptics* cannot be simultaneously be coded as *auditory + visual*, as it already includes these senses.

Study Design describes the methodology as well as tasks used for measuring and acquisition of data in a conducted study. The *Study Design* is divided into *Setup*, *Data Types*, *Method*, and *Task*. We distinguish between the types of study *Setups* as *lab study* (n=61) and *field study* (n=2). The *Tasks* are divided into seven task types: *assembly* (n=36); *placement* (n=12); *operation* (n=9); *repair* (n=7); *search* (n=10); *playing* (n=5); *design* (n=5); and *functionality test* (n=8), which represents small tasks that test a specific functionality of the prototype. In addition to the different tasks, we coded the used *Materials* in a task. The identified material codes are *dummy material* (n=46); *realistic material* (n=27); and *continuous material* (n=2), which refers to a material that does not have a discrete size as it can be seamlessly modified in all dimensions. For methods in the study design we identified the use of *questionnaires* (n=42), *interviews* (n=27), *conversation records* (n=31), *quantitative tracking* (n=15), and *heuristics* (n=14). Lastly, the measured *Data Types* are split in *task performance* (n=39), *behavioral measure* (n=18), *perceptual measure* (n=31), as well as *presence* (n=11) and *workload* (n=8) as a specific types of *perceptual measure*. None of these codes is exclusive, as a work can conduct multiple studies and measure different *Data Types*, using different *Tasks* and *Methods*.

Recommendations describes the kind of recommendations or takeaways a work gives for future researchers. A work can give recommendations of different types at the same time, or none at all. We differentiate between four recommendation types: *hardware recommendation* (n=7); *design recommendation*; *research recommendation* (n=10); and *methodology recommendation* (n=3).

4 Discussion

In the following, we discuss our results and the current state of research in the field of remote collaboration on physical objects. Therefore, we highlight the research and technology trends derived from our survey. Second, codes that hint to research gaps are reviewed and condensed in table 2. Lastly, the relationships between codes are analyzed. We complement notable findings with exemplary research questions that could conclude from our analysis. This is not an exhaustive set of questions, but rather a first step in the direction of future work.

4.1 Research Trends and Technologies

In order to identify trends in our selected publications, works were first analyzed in respect to their publication date.

Relationship between publication counts and introduction of technologies. A constant increase in research on remote collaboration on physical objects can be observed, which is visualized by a trendline in the upper part of figure 1. However, we note that until 2006 very little work did happen in this field of research, possibly because of limited technological feasibility of capturing, augmenting, and transmitting physical content in a reasonable quality. While the overall publication count increased afterwards, the years 2010, 2014, and 2017 strike for low amount of works in comparison to the adjacent years. One explanation could be the introduction phase of novel technologies, where they are adapted in prototypes and evaluated with user studies, leading to publications 1-2 years later. Notable increases of publication counts happened around the years 2007 (the first batch of multiple works), 2012 (after the drop in 2010), and 2018 (after the drop in 2017), which could be tied to upcoming devices at that time. A constant in the technologies is the 2D screen.

The batch of works emerging in the years 2005 to 2009 shows the first introduction of mobile devices [76], projectors [36, 76], immersive AR [98, 56, 17], and Tangible User Interfaces (TUIs) coupled with AR [56, 98]. Most of the other research was done using 2D screen setups, especially on gesture supported collaboration in the context of guidance, studied extensively by Kirk et al. [44–47]. The ARToolkit [34], a marker-based tracking approach first presented in 1999 and released as an open source variant in 2005, came up in this timeframe and was used for early collaborative AR works [56, 17]. The increase of publications from 2012 to 2016 appears to be related to the introduction of the Kinect camera by Microsoft [65], which was first released in 2010 and found its way into academia around between 2011 and 2012 [100]. Especially from 2012 to 2014, 8 out of 18 publications utilized the Kinect [90, 11, 2, 3, 85, 88, 86, 57]. In addition, depth-sensing systems were coupled with projector systems to enable a seamless interaction with physical content [2, 3, 85, 86, 11]. Technology use between the years 2015 and 2016 was more fragmented, but notable is the use of immersive VR headsets [6, 72, 25]. A prominent example of VR headsets of that time is the developer kit 2 of the Oculus Rift, released one year prior (2014 [71]) and used by Gao et al. [25] and Amores et al. [6]. The latest increase in publication counts, starting from 2018, may be related to the rise of Head-mounted Displays (HMDs), especially the HoloLens AR headset [64], which was first released in 2016. It was used in numerous works published since then [28, 37, 38, 61, 94, 31, 84, 91, 92]. The high amount of publications is currently lasting, possibly related to the hardware trend of combining VR and AR that can be observed in multiple works from 2020 and 2021 [28, 37, 43, 94, 93].

It can be stated that the research community usually rather adapts off-the-shelf devices than developing costly novel technical prototypes. We understand the traceability of publication numbers to hardware launches as a sign that research on remote collaboration on physical objects is still highly dependent on new technologies, which are yet to open many opportunities in that field.

Prominence in technologies. We were able to identify a diversification of device use, correlating with publication counts, visualized in figure 1. The most prominent technology found in this survey is the 2D screen, as it is embedded into commercially available and long-time established technologies, such as laptops and mobile devices. Its widespread use could come from the maturity of the technology, as well as from its relevance for both personal and professional use in the form of video assistance. The different applications of video technology are studied extensively in CSCW literature as video-mediated collaboration, regarding visibility as a crucial aspect of collaboration. While we anticipate the high relevance of 2D video and 2D screens, the technological trends observed in this survey hint towards more immersive 3D representations of spatial content. Even though their fidelity is yet limited, they allow for a more natural experience, better understanding of spatial relationships, and free perspective, as highlighted by multiple publications [25, 26, 11, 90, 89]. However, researching a new technology in a collaborative scenario requires the technology to mature, which can lead to a temporal shift in research. Accordingly, it remains to be explored how novel technologies can be quickly embedded in prototype environments, so that they can be used to explore collaborative scenarios.

AR appears like an obvious choice for adding collaborative features to the real world and is used in 19 works (24%). In our selection of publications, we found AR plus VR setups [25, 26, 28, 43, 89, 92], AR plus desktop setups [38, 61, 42, 84], and AR plus AR setups [98, 31]. Optical see-through HMDs and video see-through AR/VR HMDs are equally in use. Overall, the research field seems to keep on adopting and experimenting with novel technologies. In its cause, we see multiple research topics related to collaboration being studied repeatedly under different technological conditions. This leads to the question if existing problems of remote collaboration on physical objects are being solved by novel technologies, or them being merely explored anew in the context of another technology. An example is the independence of viewpoints, that was investigated with projector setups [30, 2] as well as with immersive AR [89, 42].

Similar to our work, Wang et al. studied the use of immersive displays in their work on AR/MR-based co-design from 2020, in which they further differentiated the type of immersive HMDs and presented a diverse view on available technologies [95]. Unlike our results, their analysis showed a decline of head mounted displays in favor of desktop, handheld, and projector-based solutions. However, in the field of remote collaboration on physical objects, we can state a decline of projector-based solutions after year 2016 and a current increase in head-mounted displays. The exploration of suitable technologies is in line with the findings by Wang et al., who state that 37 percent of their reviewed works were dedicated to comparing AR/MR technologies [95]. The low number of 7 *hardware recommendations* (9%) made throughout our publications further indicates that authors are hesitant to present a technology as a potential solution.

To summarize properties of relevant technologies, the technologies highlighted in figure 1 and their most common use in the investigated literature are condensed in the following. The 2D screen provides video-based collaboration at a high resolution [24, 13, 70]. Its limitations are reached for depth perception and providing tangible experiences. Mobile devices as a variant of 2D screens allow for more flexible video-based collaborations [39, 15, 66]. Projectors can merge their output with physical content, thereby bringing remote places closer together [4, 76, 41], but are prone to light influences and complex in their setup. Immersive VR allows for real depth perception and more natural inputs [94, 37, 26]. Related to VR, immersive AR provides information directly in conjunction with the physical content [89, 31, 91]. Both, VR and AR are currently limited in their capabilities of streaming and representing remote physical environments at a high fidelity [50, 2, 26]. Lastly, TUIs are built on haptic in- and output, but are comparably niche to this date. They can be combined with other technologies to present more information [56, 57, 80].

4.2 Identified Research Gaps

Regarding this paper's research question of "what aspects of remote collaboration on physical objects have been explored in scientific literature", we review the codes obtained from our literature selection for striking numbers. While an infrequently occurring code does not necessarily indicate a research gap, it can serve as an indicator of under-researched areas, especially when accompanied by a highly represented counterpart. At first, codes that did not hint towards a research gap and showed expected occurrences are named without further elaboration. *Application Area* showed similar results to thematically adjacent literature reviews [75, 60]. For the *Study Design*, most codes returned expected numbers, like *assembly* tasks being used most often [75] and *task performance* as well as *perceptual measure* being the prime measurements in conducted studies. Lastly, the determined tracking technologies, such as *marker-based tracking*, *eye gaze tracking*, and *head tracking*, were mostly in line with expected outcomes [95, 75, 12]. Beside code appearances aligning with related work, some of the codes we recorded showed little significance and are therefore not further discussed. Among these codes are *Input Devices*, *static* and *portable Prototype Setups*, as well as prototypes capable of capturing *large scale* or *small scale* environments. In the following, potential research gaps are presented in thematically related combinations, as described in section 4.3.

Physical properties of objects in collaborative settings. Regarding *Research Focus* and its sub-codes, it becomes apparent that with 58 works (73%) most of the research is *User*-targeted, thereby addressing potential user-related challenges during collaboration. An example is the management of different viewpoints and the correlating effects, e.g. [24, 42, 89, 30, 70, 83]. While a research focus on the collaborating user is valuable, it does not address the existing challenges of representing and interacting with physical objects over distance. In contrast to the *User*-focus, only 8 works (10%) focus on the *physical object* as a part of collaboration. When taking works into account that regard the *object interaction* and eliminating document intersections, still only a limited amount of 13 publications (16%) can be found. While an *environment*-focus regards the physicality of the world, it is most often dedicated to challenges that are tied to scene capturing, transmission, and reconstruction of bigger surroundings [2, 26, 91]. Therefore, we interpret this as an alternative research direction compared to a focus on physical objects. Regarding the difficulties in both, representation and interaction with remote physical objects, our results indicate physical object focus being a research gap in remote collaboration. It remains to be seen, how the research focus can be moved onto the physicality of objects, in order to diminish the barrier between co-located and remote work.

We further investigated the sensory channels of collaborators that are addressed by a publication's prototype. It is apparent, that in contrast to the visual sense, haptics, as the main sensory complement provided by physical content through its tangibility, is only regarded in 9 publications (11%). This is in line with the lack of focus on physical objects, discussed in section 4.3, as well as with the findings of Schäfer et al., who conclude that the majority of works in the field of VR, AR, and MR utilizes the audiovisual senses with tangibility only being rarely addressed by AR systems in case of applied markers [87]. The question rises, how research can be encouraged to study the tangibility of physical objects as part of a collaboration, since it is the sensual perception physical objects provide compared to digital ones. One explanation for the low representation of haptics is the use of established technologies, such as video conferencing [61, 24, 68], which rely on the visual sense in combination with audio without being capable of supporting haptics. Accordingly, haptics-simulating technologies, e.g. force-feedback gloves [77], are still highly experimental and were not found in our literature survey. Instead, we identified 8 TUIs (10%) [14, 31, 57, 56, 78, 80, 98, 27] as ways of seamlessly merging physical with digital content while providing passive haptic feedback. This approach could become increasingly relevant for remote collaboration on physical objects in the future. We further justify this expectation by the trends of technologies, discussed in section 4.1, that allow the interweaving of real and digital content, e.g. MR coupled with a TUI [31].

Another code that emerged is the kind of physical *Material* used in study tasks conducted with prototype systems. Both *dummy* and *realistic materials* were used in similar amounts. In contrast, *continuous materials* such as clay, that differ from part-based discrete materials like LEGO bricks, occurred only twice (3%) [70, 50] (clay and foam carving respectively). While many prototype systems could also support continuous materials, their use could result in different outcomes in some cases. It could be of interest to research into the use of continuous and flexible materials in remote collaborations in the future, as they seem to be the most challenging materials besides the fluids.

Mutual, Multiuser and Asynchronous collaborations are underrepresented. An apparent imbalance of codes can be found in the codes *dyadic* and *multiuser*, parented under *Collaboration Type*. Only a single publication exists that explicitly researches the case of more than two remote parties collaborating [74]. While other prototypes and systems might be able to support a multiuser collaboration with adjustments, its use and resulting consequences are usually not studied. This is in contrast to everyday practices, where work on physical objects is often done by more than two people simultaneously, for example if we think of a car being repaired in a workshop.

Regarding *Collaboration Type*, it can be stated that the majority of works examine a *guidance* scenario, adding up to 62 works (77%). In most of these expert-worker scenarios, the prototypes consist of *asymmetric* systems (*Prototype Setup*), which add up to 60 publications (75%). When comparing the amount of guidance scenarios to the 17 *mutual* collaborations (21%), it can be concluded that the latter is a rather underrepresented scenario. This possibly results from the nature of physical content being present in one place and therefore difficult to share, manipulate, and access from remote, while the use case of one person observing and guiding another person to do a task is much easier to accomplish. While the related literature surveys do not state a similar finding, the existence of dedicated literature on training [59] and guidance [53] in MR environments indicates bigger amounts of research in these areas. We conclude that there appears to be a research gap on the mutual collaboration on remote physical content. In line with that, further research could investigate how to equip remote collaborators with equal access rights to physical objects, to allow for mutual collaboration regardless of the objects' location.

Even though training is a unidirectional collaboration type similar to guidance, only 3 papers (4%) delved into this scenario [94, 50, 92]. This is in contrast to fully virtual setups, such as used in VR, where training is one of the main use cases [82, 97]. We assume, that the process of teaching and learning is difficult when the required physical content is not available on both locations, as the trainer or the trainee might not be able to perform an action due to missing artifacts. Alternatively, when physical objects are available, the fidelity of a presentation might not be high enough to emulate co-located training, in which case additional video might be necessary [50]. This assumption is similar to the findings of Limbu et al. in their literature review from 2018, in which they point out the missing sensors for capturing parts of the expert's performance [59]. Complementing their conclusion, we consider training with shared physical objects to be an interesting area of research.

Lastly, a notable discrepancy between *synchronous* and *asynchronous* collaboration was found. While asynchronous collaboration dominates our professional practice, it becomes apparent that asynchronous remote collaboration on physical objects is a research field that is strongly underrepresented and that synchronous collaboration is taken as the default case. It remains to be explored in what context asynchronous collaboration on physical objects is preferred. Only a total of 6 works (8%) [78, 16, 49, 50, 96, 27] dealt with an asynchronous collaboration scenario. While many approaches of synchronous work might be transferable to asynchronous collaboration with some adjustments, we report the asynchronous remote collaboration on physical objects as a promising research field to be explored. Since synchronous collaboration on physical objects is so prevalent, the question rises how we can adapt existing findings to asynchronous collaboration. This is in line with the findings of Pidel and Ackermann, who also stated the under-representation of asynchronous collaboration in their survey on VR and AR [79], as well as with the recommendations of Belen et al., who attribute potential for research on asynchronous collaboration [10]. While these two literature surveys assess the need for research on asynchronous collaboration in regard to MR technologies, we further emphasize the challenges of implementing asynchronous collaboration with physical objects that are manifested in a non-dynamic state. We conclude that most reviewed publications regard a synchronous collaboration, while the asynchronous collaboration on physical objects appears to remain a research gap.

4.3 Code Relationships

Besides the identification of research gaps in section 4.2, we analyzed co-appearances of codes. This analysis is visualized as an alluvial diagram, which is shown in figure 5 and discussed along it.

Support for tangibility is influenced by research focus. We detected co-appearances between the codes *Research Focus* and the human senses a system addresses. The code *auditory (only)* was stripped, as it is used as a control condition in addition to visual information, instead of being an independent condition. The most common research focus is the collaborating *User*, which results in targeting the *auditory and visual* senses without regarding the haptic sense in all works but one. In comparison, if the *physical object* or *object interaction* are the research objective, the haptic sense is addressed in more than half of the works. It surprises, that works researching the collaboration on an *environment* also do not regard the haptic sense. This could be attributed to the fact that most of these publications are concerned with challenges such as the reconstruction and transfer of 3D environments [2, 25, 88, 50]. As a research focus on users usually does

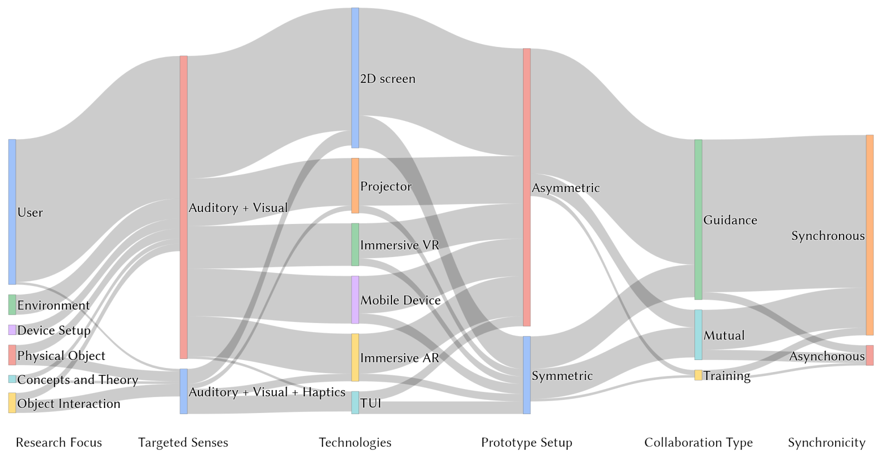

Fig. 5. The alluvial diagram highlights the relationship between prominent codes that stand out due to notable occurrence numbers and are part of this paper's discussion. The codes on the x-axis are abstracted categories from the detailed codes on the y-axis. It highlights, for example, that in most works that utilize an asymmetric prototype setup a guidance scenario is regarded, while symmetric prototype setups are rather used for mutual collaborations. It also reveals that this relation is not exclusive, meaning that asymmetric setups are also used in mutual collaboration and vice versa.

not regard the haptic sense during a collaboration, it appears to be even more important to put the focus on the artifact itself to support tangibility in remote collaborations on physical objects.

When taking a look at how the *Targeted Senses* are connected to the used *Technology*, it becomes apparent that neither *immersive VR* nor *mobile devices* are used in systems that address the haptic sense for both collaborators. This does not mean that there are no prototypes using immersive VR or mobile devices that have a high proportion of physical interaction [39, 29, 80], but that the topic of allowing a remote collaborator to experience a haptic sensation through these technologies is not regarded. In comparison, the technologies *2D screen*, *projector*, and *immersive AR* are often used as a supplement technology to systems that allow for haptic interaction [31, 56, 57]. A promising research direction appears to be how existing technologies, such as mobile devices and VR, can be enhanced to support remote tangibility.

Prototype Setup and Collaboration Type are related, but not dependent on each other. Technology does not dictate whether a prototype system is set up as an *asymmetric* or a *symmetric* system. Each technology is used in similar proportions in both constellations, according to the distribution of asymmetric and symmetric systems, with a large tendency towards asymmetric setups. However, it can be stated that in the case of TUI, the proportional distribution between asymmetric and symmetric differs from the average distribution, as TUIs are used in symmetric systems in half of their implementations. Besides this excep-

Codes *that are under-represented*	**Existing Approaches** *based on search query*	**Exemplary Research Questions** *to address research gaps*
Asynchronous Collaboration	· Documentation of physical work steps [12] · Trace-based steps in TUI environments [21] · Tangible interface with digital access [61] · Spatial capture of a MR telepresence system [42] · Asynchronous audio/video-conferencing [40] · Using commonly available physical proxies [77]	In what context is asynchronous collaboration on physical objects preferred over the current default use case of synchronous collaboration?
Multi User Collaboration	· Switching between novices in video-training [74]	How can existing findings for synchronous collaboration on physical objects be adapted to asynchronous collaboration?
Mutual Collaboration	· Bi-directional gaze cues [37] · Distributed teams build physical components [13] · Open source documentation to rebuild an object [16] · Shared or independent view on shared object [42] · Physical proxy objects can be shared and exchanged [98, 96, 56] · Simulating, mirroring, and synchronizing physicality of two places [11, 14, 20, 31, 41, 57, 70] · Bidirectional Mixed Reality telepresence [50] · Mutually managed video-stream usage [40] · Managing access rights to distributed TUI artifacts [27]	How to equip remote collaborators with equal access rights to physical objects, to allow for mutual collaboration regardless of the objects' location?
Focus on Physical Object	· Capturing and projecting physical objects [36, 41] · Augmenting physical proxy objects [56, 98] · Synchronize physical distributed twins [14] · Physical LEDs for collaborative highlighting [51] · Lightfields for object representation [66] · Version control for physical objects [78]	How can the research focus be moved onto the physicality of objects, in order to diminish the barrier between co-located and remote work?
Haptic sense targeted	· Proxy objects providing passive haptics [56, 98] · Passive haptics due direct interaction with synchronized actuated objects [14, 20] · Distributed physical objects providing passive haptics [96, 13] · Tangible input for both collaborators[31] · Tangible output that can be interacted with [57] · Distributed tangible surfaces [27]	How can research be encouraged to study the tangibility of physical objects as part of a collaboration, since it is the sensual perception physical objects provide compared to digital ones?
Continuous material support	· Capturing continuous material via video [70] · Representing continuous material through 3D capture and video [50]	How is remote collaboration on physical objects influenced by continuous and flexible materials instead of discrete parts?

Table 2. Overview of underrepresented codes hinting at research gaps, existing approaches in these areas, and exemplary research directions that could address these research gaps. This table can be used as quick reference to the main findings of this work regarding potential research gaps.

tion, asymmetric setups are highly favored, which is in line with the findings of Schäfer et al., who state that MR setups are usually asymmetric since the input modalities are often not symmetric [87].

When comparing *Prototype Setup* and *Collaboration Type*, *asymmetric* systems are favored in *guidance* tasks, as expected. Similarly, *symmetric* systems are rather used for *mutual* collaborations. We note that nevertheless, both, asymmetric and symmetric setups, can be used to support the opposite collaboration type as these combinations can be found in 20 works (25%). This proposes the question, which properties of a system lead to it becoming an asymmetric system supporting mutual collaboration, or it becoming a symmetric system supporting a guidance scenario. Regarding the *training* code, there is no tendency in using an asymmetric or symmetric setup, as the amount of occurrences is too small to identify a clear relation.

Finally, we split up the code *Collaboration Type* into the collaborative action and the synchronicity of collaboration. It can be stated that all three collaborative actions: guidance, training, and mutual, are supported in synchronous and asynchronous collaborations. We cannot confirm any further relations, other than the low amount of publications regarding asynchronous collaboration consisting of guidance and mutual collaboration types to equal parts.

5 Conclusion

In this paper, we studied 80 publications in the field of remote collaboration on physical objects in the form of a structured literature review. The publications were coded in an open coding approach. Regarding technology trends, a diversification of technologies can be observed, with immersive head-mounted-displays being currently on the rise. By analyzing the created codes, we made the following findings about existing research gaps in that field: There is a general lack of research focus on the physical object as a component of collaboration. Further, the physicality of the object and the haptic sense of collaborators are identified as research gaps. We found a low amount of symmetric prototype systems and training scenarios utilizing shared physical artifacts. Mutual collaboration, multiuser collaboration as well as asynchronous collaboration were found to be poorly represented, posing many opportunities for further research. By analyzing code relations, we confirmed the relation between the lack of research focus on physical objects or object interaction and a low amount of works regarding haptic senses. We also found that the research gap of asynchronous collaboration is neither related to the design of the prototype nor the technologies used, but rather due to a lack of work in that field. Lastly, we reviewed the current state of research on remote collaboration on physical objects in the context of computer-supported cooperative work. Besides an overview of existing literature and research gaps worth to investigate, we provide a set of potential research questions for future work. Additionally, we emphasize the need for further research and discussion in the area of remote collaboration on physical objects.

Appendix

Extended Method

As supplementary material, we provide an extended version of the method, to allow for reproduction of our results by other researchers. This includes formulating a research question, creating a search query, and filtering the results in a structured and comprehensible way. Similar to prior SLRs [60, 8, 69], we follow the guidelines defined by Kitchenham's work "Procedures for Performing Systematic Reviews" [48]. The goal of this SLR is to gain an overview of existing work that addresses computer-supported remote collaboration on physical objects.

Research Question

We formulate the research question for this survey as: "What aspects of remote collaboration on physical objects have been explored in scientific literature?". The research question will be answered by reviewing work in this field of research using an unbiased approach [48].

Search Strategy

For the extraction of publications, the ACM digital library [1], SpringerLink [5], and IEEE Xplore [35] were selected as databases, since they are the databases used most frequently by related literature surveys as well as most relevant to HCI research. Based on relevant sample publications, the minimal query *"remote collaboration" AND ("physical task" OR "physical object")* was build, yielding a total of 322 search results. In order to broaden the search and to decrease chances of missing publications, the query was extended by similar terms and synonyms. The full extended query chosen for extraction of work was: *(cscw OR "computer supported collaborative work" OR "tele-collaboration" OR "distributed collaboration" OR "remote cooperation" OR "remote collaboration") AND ("physical task" OR "physical object" OR "tangible object" OR "physical artifact" OR "physical computing")*, yielding 1093 results across the three libraries. The total of 1093 search results were composed of 317 results for the ACM digital library, 771 results for SpringerLink, and 5 results for IEEE Xplore. The query was not limited to specific fields of database entries, but could be found anywhere in a record. The search was performed in late 2020 and refreshed mid 2021.

Filtering

The results of the search query were neither filtered by conference nor by publication date or relevance metric. By the removal of duplicates and non-papers, the total amount of results was reduced to 829. Afterward, the entries were reviewed by one researcher, skimming title and abstract. 116 publications were selected for full text analysis.

For decision-making in the full text filtering process, multiple inclusion criteria were more precisely phrased by two researchers. This made it easier to decide on in- or exclusion of a work and made our selection process more comprehensible. In addition to the existing selection properties from the search query, the following criteria were derived:

– A minimum of two persons are part of a collaboration.
– The collaborators are physically distributed.
– The topic of the collaboration must be a physical object, which is three-dimensional.
– The physical content must be altered in some way during collaboration.
– The collaboration goes beyond verbal instructions, targeting at least one additional sense (visual or haptic).

These five filtering criteria each rose from literature that could fit the term "Remote Collaboration on Physical Objects", but would stretch the definition of such. For example, the collaboration should consist of actual people collaborating, a human collaborating with a remote system but not with another person was therefore excluded. Some works investigated co-located collaborators working together, which does not investigate the difficulty of physical separation and physical content. Some works investigated remote collaboration on digital content or physical but abstract representations, such as two-dimensional documents or sketches, instead of including the actual three-dimensional physical object. Collaboration should involve some form of modification of objects, like altering its shape, position or rotation, to avoid static discussion. In order to exclude works that examined telephone support, more senses than the aural one have to be targeted.

Based on title and abstract, each entry was labeled as fitting, not fitting, or unsure. Publications that were marked as unsure were skimmed using full text and re-marked as either fitting, not fitting, or still unsure. Edge cases and papers that remained labeled as unsure, were in- or excluded after internal discussion by three researchers. From the 116 publications, a total of 76 papers were approved for further analysis at the time of the first search.

The final iteration of our coding process overlapped with the release of the CHI program in 2021. To the best of our knowledge, this was the only conference program that was released at the time of coding - from the list of relevant conferences that we had already synthesized during earlier coding rounds. Due to the high confidence we had, at this point in the coding process, on what relevant conference venues were for our literature review, we decided to include the papers from the CHI conference that matched with our search query keywords. This resulted in the inclusion of 4 additional papers in the last coding stage, increasing the amount of publications from 76 to 80.

We followed the proposed procedures of Barbara Kitchenham to the best of our knowledge. As described by Kitchenham, the approach has some natural limitations, such as the remaining chance of missing relevant literature and the existence of a natural bias of researchers [48]. However, we are optimistic about the selected literature as well as our results being representative of the field of remote collaboration on physical objects to this date.

A history of the selection process is presented in table 3. It is further visualized in figure 6. A complete list of retrieved publications can be found in table ??. This list also holds information about the kind of contribution a publication made, as well as their main findings.

	query result	valid content	after title and abstract	after full text	late additions
ACM DL [1]	317	305	67	52	52+4
SpringerLink [5]	771	519	44	21	21
IEEE Xplore [35]	5	5	5	3	3
total	1093	829	116	76	80

Table 3. Filtering process partitioned by databases. The total of 1093 publications were reduced to a selection of 76 publications in four stages. Four papers were added subsequently, resulting in a total of 80 publications.

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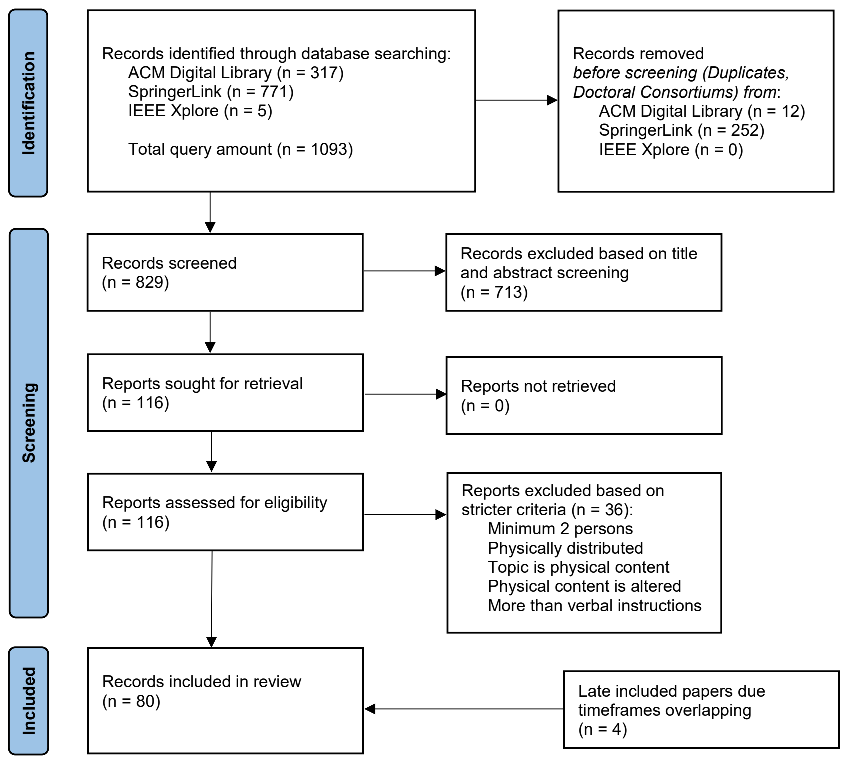

Fig. 6. PRISMA diagram of the selection process. Starting from 1093 publications, the amount of works was reduced in multiple steps down to 76 works. Four papers were added subsequently, resulting in a total of 80 publications.

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