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A Systematic Literature Review to Characterize Asymmetric Interaction in Collaborative Systems

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Abstract

Computer-mediated collaboration often relies on symmetrical interactions between users, where all the collaborators use identical devices. However, in some cases, either due to constraints (e.g. users in different environments) or by choice (e.g. using devices with different properties), users engage in asymmetrical interactions. Addressing such asymmetries in heterogeneous systems can be difficult as there has been no systematic analysis of how to define them, or their impact on collaboration. In this paper, we characterize the asymmetries that can arise between users' interactions within collaborative heterogeneous systems. To this end, we conduct a systematic literature review of asymmetric collaborative systems, coding their properties, including the interaction spaces, their input and output modalities, and shared feedback. We then define the dimensions of asymmetry that emerge from this review. We discuss their impact on collaboration and outline a set of challenges and opportunities for future research.

CCS Concepts

• **Human-centered computing** → Human computer interaction (HCI); Interaction paradigms; Collaborative interaction.

Keywords

Remote collaboration, asymmetric interaction, systematic literature review

ACM Reference Format:

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1 Introduction

Traditional computer-mediated collaboration in desktop environments often relies on symmetrical interactions, as all users employ

WIMP (windows, icons, menus, pointer) systems [80]. However, in other cases, users employ different interactions, as when collaborating with heterogeneous systems. By heterogeneous system we refer to a system that combines a diversity of display and interaction devices, such as tabletops, walls, and head-worn augmented reality (AR) or virtual reality (VR) devices. Heterogeneous systems are being extensively explored to facilitate the collaborative decision-making process in complex contexts [67]. For instance, in a crisis management room, a large display can provide a shared overview of the crisis area to all on-site stakeholders, while local or remote experts can use personal and head-worn devices to access more detailed or immersive views [12]. All these differences are referred to by a large variety of different names in the literature, such as asymmetries [92], dissimilarities [24] or incongruent spaces [19]. In this paper, we refer to these using the word asymmetry.

These asymmetries might be due to constraints, such as users being in different environments with different interaction capabilities, but may be also used by choice, for instance, to provide the appropriate interaction modalities for each stakeholder. Interestingly, these asymmetries can positively and negatively impact the user's interaction: they can contribute to a better role distribution among stakeholders [17] but they may hinder workspace awareness [6]. For instance, when one user is on a desktop and another is using a VR headset, it can be challenging to accurately represent each other's actions on their respective displays. Their input devices differ significantly (mouse vs. VR controller tracked in space), their displays have different dimensionalities (2D vs. 3D), and they navigate the shared workspace at different scales. We define all these as asymmetric interactions: *by asymmetric interaction, we refer to an interaction with the collaborative system (e.g. input, output, content) that is different between two users*. Previous work on asymmetrical collaboration has either proposed solutions to particular problems (such as the difference in display layouts [19]) or studied the impact of a given asymmetry on collaboration. While a few papers have theoretically addressed the concept of asymmetry in collaborative systems, to date, there has been no systematic analysis of how to define and describe these asymmetric interactions, nor what is their frequency or their impact on collaboration.

The main objective of our work is to define and characterize the dimensions of such asymmetric interactions in collaborative systems, i.e. among multiple users collaborating with a shared goal. *We use the term Dimension to refer to the different axes or attributes*



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that compose an asymmetry. We focus on them to clarify the multifaceted nature of asymmetries. By providing a unified framework, our first objective is to bring clarity and streamline the terminology used to refer to these situations in the literature. This will enable more effective communication and foster a common understanding across practitioners and researchers. Characterizing the dimensions of asymmetric interactions and linking them to previous studies can also be of value to the designers of collaborative systems, which are facing a lack of a coherent foundation on such asymmetries.

To this end, we conducted a systematic literature review (SLR) on asymmetric interaction in collaborative systems. We adopted the guidelines defined by Kitchenham [45]. We defined three keywords (collaboration, asymmetric, system) along with terms with similar meanings to query a set of well-known HCI conferences and journals. We excluded non-archival papers as well as papers without a functional prototype, with only temporary asymmetrical interaction, or with no collaborative activity. Among the 297 papers initially identified, our final corpus includes 46 papers presenting 57 systems. Although our approach was domain agnostic, a majority of the retrieved papers involve mixed reality (XR): this can be attributed to our focus on papers presenting functional systems, as well as recent advances in XR technologies and their application to collaboration. We analyzed the systems presented in these 46 papers by coding the collaborative tasks, interaction spaces, input and output modalities, as well as their shared feedback. *By shared feedback, we refer to the feedback that reveals information about individual activities to other participants (in other interaction spaces) [16].* From this analysis, we were able to identify 8 dimensions of asymmetry: input modality, output modality, dimensionality, mobility, display space, content access, content layout and shared feedback. For each of these dimensions, we provide a definition, report on their prevalence in our corpus of papers, and present some examples illustrating their impact on collaboration. Finally, we discuss the future challenges and opportunities related to asymmetric interaction in collaborative systems.

To sum up, our contributions are 1) a systematic literature review on asymmetrical collaborative systems, 2) a characterization of the dimensions of asymmetric interaction, and 3) a set of design challenges and opportunities for future research on asymmetric collaboration.

2 Background

In this section, we provide an overview of previous literature reviews on collaboration, existing models of collaboration focusing on interaction with heterogeneous systems as well as previous work focusing on the theories of asymmetrical collaboration.

2.1 Systematic Literature Reviews on collaboration

Previous systematic literature reviews (SLR) have focused on different aspects of collaborative environments. Some of them focus on specific application areas, such as the SLR by Van Der Meer et al. [85] on collaborative learning in virtual reality. Their coding categories focused on the educational aspects, the system and its evaluation. Other SLRs focus on specific devices or environments, such as the review on collaboration on large interactive displays

by Mateescu et al. [52]. Their coding focused on the collaboration process, the contextual information and the outcome of the collaboration. Ghamandi et al. [21] recently conducted an SLR on collaborative XR tasks, describing the action and system properties (such as the time-space or location).

The crucial question of awareness has been the subject of other reviews. The review on awareness in collaborative systems by Lopez et al. [51] classified papers using different usual characteristics of collaborative systems, such as the time-place matrix. More relevant to our work is the recent literature survey by Assaf et al. [3], leading to a taxonomy of workspace awareness and visual cues in XR collaborative systems. Their description of the collaborative situation included eight features and two of them had a “symmetry” property: the setup (i.e. the blend usage of different levels of the virtuality continuum) and the role (the privileges that users have using the collaborative system).

In the specific field of mixed reality (MR), where asymmetric interaction is more likely to happen, Schäfer et al. [75] surveyed synchronous MR remote collaboration systems. They created a taxonomy with three categories: environment, avatars and interaction. Within the environment, the taxonomy mentions that MR-based systems often have asymmetric inputs (e.g. keyboard and VR controllers). Pidel et al. [64] reviewed papers on collaboration in VR and AR, with a specific focus on synchronous vs asynchronous interaction. Radu et al. [68] reviewed needs for AR collaborations in collocated spaces: they collected seven collaboration needs and one of them is that users need to share the same environment, i.e. see the same virtual content. Ens et al. [18] reviewed collaborative MR systems in 2019 and one of their six coding properties concerned symmetry, defined as “whether collaborators have the same basic roles and capabilities”. They found that 41% of papers were symmetric and 57% asymmetric.

Although not specifically focusing on collaborative systems, Brudy et al. [9] conducted an SLR leading to a taxonomy of cross-device systems. Some of the dimensions of their taxonomy are related to collaborative interaction, such as the Relationship (the number of users from single to multiple), the Scale (near, personal, social or public) and the Space (co-located or remote).

In these previous SLRs on collaborative environments, the interaction asymmetry is mentioned but only considered for specific factors or not sufficiently refined. To sum up, previous SLRs have overlooked the question of asymmetry, leaving a significant gap in our understanding of its state in current collaborative systems, and its implications.

2.2 Collaboration using heterogeneous systems

The domain of collaborative computing in HCI has produced a significant number of models and frameworks since the seminal definition of groupware by Johansen [38], focusing on the multiple aspects of collaborative systems: time-space matrix [37], workspace awareness [28], territoriality [77], etc. Covering the entire space of these previous models is beyond the scope of this literature review. Instead, we provide an overview of those models related to either interaction or collaboration using heterogeneous systems, where the concept of asymmetry is more relevant.

In their model on mixed-space collaboration, Grasset et al. [23] identified five types of collaboration according to whether users shared the same environment and viewpoints. Neumayr et al. [57] developed Domino, a framework to describe hybrid collaboration in partially distributed teams. They defined hybrid collaboration as a collaboration that switches back and forth between all four quadrants of the time-space matrix, involving more than two collaborators, who employ different tools and devices during collaboration. They proposed a set of hybrid coupling styles according to whether users shared the same or different information, physical displays, and problems. These styles stem from Isenberg’s original description of mixed-focus collaboration as a series of phases of tightly-coupled or loosely-coupled collaboration styles [34].

Schröder et al. [76] proposed a framework describing transitional interfaces, i.e. where users move along the reality-virtuality continuum during collaboration. Although their paper mentions asymmetrical levels of reality-virtuality (i.e. VR-AR, PC-AR, PC-VR), their model focuses on the transitions between these levels.

The common aspect of these models is that they describe the level or type of collaboration according to how much users share the same environment, devices, viewpoints, levels of reality-virtuality and tasks. However, these works used the term “different” mainly to refer to “different instances”, which are not necessarily of a different nature. In contrast, an asymmetry is the “lack of equality or equivalence between parts or aspects of something”. Hence, these previous models did not explicitly explore the concept of asymmetry.

2.3 Understanding asymmetries in collaborative systems

Beyond the works that developed or evaluated asymmetrical collaborative systems, which we review in our SLR, few papers have theoretically addressed the concept of asymmetry in collaborative systems. Billingham et al. [7] defined communication asymmetries in collaborative wearable interfaces as “an imbalance in communication introduced by the interface used for communication, the expertise or roles of the people communicating, or the task undertaken.” Ashdown et al. [2] analyzed asymmetric synchronous collaboration in distributed teams. They considered the asymmetry in the physical environment, organizational roles and available technologies and described the existing asymmetries in an urban search and rescue scenario.

The notion of asymmetry is used in collaborative VR to describe different virtual telepresence [78], virtual movement [70] or properties of the media spaces [30]. Volda et al. [86] identified six types of asymmetries in media spaces: media, fidelity, participation, engagement, benefit and place. Combining these previous frameworks, Ouverson et al. [63] proposed a composite framework of co-located asymmetric VR. They define asymmetric VR as a “form of VR interaction in which co-located users access the same virtual environment using different kinds of technology”. Their framework describes asymmetry through 5 dimensions: spatial co-presence (the mediated access to each other), transportation (the interaction metaphors), informational richness (how the technology delivers and captures information about the MR space), team interdependence (the goals) and balance of power (the degrees of control).

To sum up, beyond the work on asymmetry in VR, we are still missing a systematic approach to define and describe asymmetries in collaborative systems.

3 Systematic Literature Review (SLR) method

We conducted a Systematic Literature Review (SLR) of papers on asymmetric collaborative systems. Unlike narrative reviews, this method reduces potential biases in paper selection and enhances both the clarity and reproducibility of the findings [31]. We adopted the guidelines defined by Kitchenham [45]. The authors of this paper were the four researchers involved in each step of this SLR.

3.1 Search strategy

Our research focuses on the dimensions of asymmetric interaction in collaborative systems. Hence, the three main research keywords added to our search strategy were *collaboration*, *asymmetric*, and *system*. Following Kitchenham’s guidelines, we added similar terms for each of the keywords to the query by using synonyms or alternative spellings. To identify such terms, we started from a dozen already-known papers related to our global line of research on collaboration using heterogeneous systems. These papers revealed that a large variety of terms were used to refer to the asymmetrical aspect, such as mixed, dissimilar, incongruent, unequal, or heterogeneous.

All query keywords were combined by ANDs and ORs to generate the subsequent search strings:

(*collaboration* OR *teamwork* OR *collaborative* OR *collaborator*)
AND

(*asymmetric* OR *asymmetrical* OR *mixed* OR *different* OR *dissimilar* OR *incongruent* OR *unequal* OR *unmatched* OR *heterogeneous* OR *unsymmetrical* OR *unsymmetric*)

AND

(*device* OR *prototype* OR *system* OR *tool* OR “*interaction technique*”)

We ran this query in the “Advanced Search” tool of two digital libraries, ACM Digital Library and IEEE Xplore. More precisely, we searched for the presence of these terms, in any order, exclusively within the abstract of the fetched papers. Hence, the query resulted in a set of papers whose abstracts contained the three terms collaboration, asymmetry and system (or their synonyms). To ensure the quality of our corpus, we retrieved papers from a predefined list of selected HCI conferences and journals (see section 3.2), which are available in ACM Digital Library and IEEE Xplore. Hence, we did not look at other databases. Since the SLR focuses on collaborative systems developed at any point in HCI history, there was no restriction to the publication year.

3.2 Study quality assessment

We limited our search to well-known peer-reviewed conferences and journals from the HCI field to ensure the quality of our corpus. Those conferences and journals are the following publication sources: ACM CHI, ACM UIST, ACM CSCW, ACM ISS, IEEE ISMAR, IEEE VR, and ACM TOCHI, all of which include a subcommittee or main topic related to collaborative interaction. Hence, we did not enforce any other quality criteria.

3.3 Exclusion criteria

We decided on four exclusion criteria to decide on the relevance of the papers retrieved by our query, respectively related to the type of publication, the system, the asymmetry, and the collaboration.

The first criterion was to exclude non-archival papers (e.g. posters, demos, workshops. . .) to avoid multiple occurrences of the same system and because the systems in such papers are usually insufficiently described and/or evaluated.

The second criterion consisted of excluding papers that did not present an implemented prototype of one or several systems, to identify the interaction devices and modalities involved in the collaboration. For instance, we excluded papers presenting only a design space or a conceptual design of a system.

The third criterion was to exclude papers that used the asymmetric term (or a synonym) to refer to aspects unrelated to the user's interaction, as we wanted to collect information about interaction asymmetry. For instance, some papers used the term "mixed" or "different" to refer to other concepts than collaboration. We also excluded papers where the asymmetry was temporary. For instance, when co-located users share multiple modalities, each user might interact with a different modality at a given moment. We took this decision to focus on clear asymmetrical situations, as any system can potentially lead to a temporary asymmetry.

The fourth criterion consisted of excluding papers in which the collaborative activity was not clearly identified. For instance, we excluded papers where multiple users share the same physical space or virtual environment without a clear common goal. In such cases, users do not need to collaborate with each other to perform the task.

The first exclusion criterion was applied automatically. The others were applied manually by the four researchers conducting this project. Each of the four researchers was assigned a set of papers to review and classify as "included," "excluded," or "to discuss" if they were uncertain. Each paper was assigned to one coder. Later, the researchers debated together whether to include or exclude the "to discuss" papers (included and excluded papers were not discussed).

3.4 Data coding

We conducted an iterative process to code the collaborative systems after the exclusion process. First, ten papers were used to come up with a first coding table: each paper was processed by two researchers independently, and each researcher processed five papers. The resulting coding tables and encoded papers from the four researchers were then compared and discussed to elaborate an enhanced and shared coding table and to agree on the encoding of the first papers. A second iteration of this process was made, with the new coding table and ten papers as well (including five from the first step). These iterations resulted in a final version of the coding table with associated written definitions for each code, used to process all the papers retrieved by the SLR after the exclusion process.

The papers were divided randomly into four groups, each group was processed by a researcher. Hence, the papers were not necessarily encoded by the researcher who included them. Then, a meeting

was held to discuss each other's coding. Finally, each system was revised to harmonize the coding of the four researchers.

Each line of the final version of the table describes one asymmetrical collaborative system. If a paper presented multiple systems, we described each one of them on a different line.

The goal of our coding was to describe the different **interaction spaces** of the systems: we define an interaction space from the perspective of the user as the interactive environment where the task is conducted, including the interaction modalities and shared feedback. Hence, two remote collaborators are necessarily in two distinct interaction spaces. In a co-located setting, two users can share the same interaction space if they share some interaction modalities (e.g. two users around a tabletop), or be in different interaction spaces if they do not share any interaction modalities. With this definition, we wanted to ensure that asymmetries are considered from the perspective of the user.

For each system, we manually coded the following data:

- Title, authors, DOI, venue, year of publication, abstract, author keywords
- General information about the system: textual description, terms used for "asymmetry", colocated or remote, number of interaction spaces, number of users, and a description of the collaborative task (objects of the task, shared content, roles of participants).
- For each interaction space: we coded the number of users and devices. For each input or output interaction of the space, we coded the corresponding modality (device and language), dimensionality, mobility (i.e. worn, fixed, movable), and sharing (individual or group use).
- The shared feedback (SF) of each space: a textual description of the SF, the presence and characteristics of avatars if used (aspect, size), and the level of sharing of the viewpoint and the environment.

3.5 Screening Process and Results

The initial data extraction was conducted in July 2024.

The query in ACM DL gave 4654 results. The ACM DL database allows filtering by content type, so we excluded non-archival types (e.g. "Abstract", "Poster", "Demonstration") and kept a total of 3059 papers (2808 "Research Articles" plus 238 "Short Papers"). We downloaded the BibTeX citations of those 3059 papers. We extracted the papers published in the publication sources of our list, resulting in 245 papers. From this set, we excluded papers from the series "CHI EA", "UIST adjunct", "CSCW companion" and "ISS companion" as those series correspond to non-archival papers. This filtering resulted in 225 papers from the ACM DL.

In IEEE Explore, we added a "*AND* (*Publication Title*:*ISMAR OR* *Publication Title*:*International Symposium on Mixed and Augmented Reality* *OR* *Publication Title*:*Virtual Reality Conference* *OR* *Publication Title*:*Conference on Virtual Reality*)" to the query to directly target the publication sources from our list. This resulted in 155 papers. Once again, we excluded non-archival papers from "(ISMAR-Adjunct)", "IEEE International Symposium on Mixed and Augmented Reality Workshops" and "Abstracts and Workshops (VRW)". We obtained 72 articles from IEEE Explore.

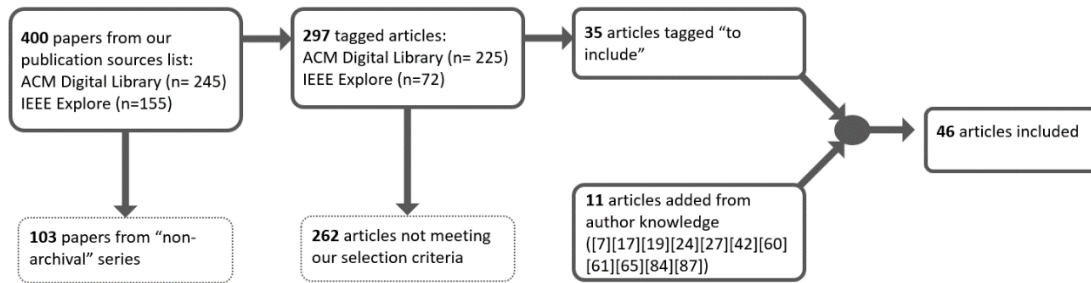


Figure 1: Overview of our screening process.

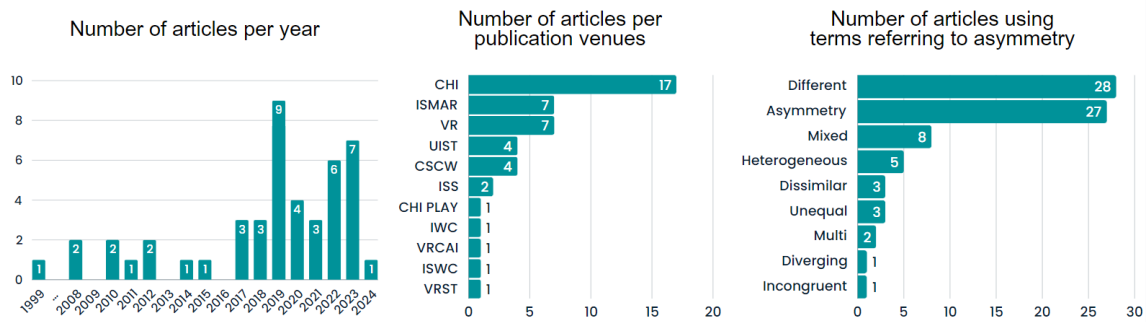


Figure 2: Number of papers in our corpus per year, per publication venue, and per term used to refer to asymmetry.

A total of 297 papers were thus selected after combining the 225 papers from ACM DL and the 72 papers from IEEE Explore. As explained earlier, these 297 papers were divided among the four researchers to decide on their inclusion or exclusion: 27 papers were tagged as “to include”, 247 as “to exclude” (following our previously presented exclusion criteria) and 23 as “to discuss”. Among the 23 papers to discuss, 15 were excluded and 8 were included. This resulted in 35 papers included at this stage from our initial query.

We then conducted a step of adding 11 papers from the author’s knowledge: 2 papers from other publication sources that are extended versions of two papers initially tagged “to discuss” that were too short to be correctly analyzed, and 9 other papers we knew of that were not retrieved by the query. As a result, in total, our final analysis was conducted on 46 papers. The screening process is illustrated in Figure 1.

4 Overview of our SLR corpus

In this section, we provide an overview of the corpus resulting from our systematic literature review, i.e. the encoding of our corpus of 46 papers. We first present an overview of the analyzed papers and then a synthesis of the properties of the 57 collaborative systems described in these 46 papers.

4.1 Overview of analyzed publications

Historical perspective: The references to the asymmetric aspect of collaborative systems appear to be relatively recent. The papers in our corpus were published after 2008 (except for one in 1999), with

a maximum of 2 articles per year until 2016, while 36 articles were published since 2017 (see Figure 2-left).

Publication venues: Most of our 46 papers come from ACM CHI (17 papers), IEEE ISMAR (7) and IEEE VR (7), as illustrated in Figure 2-center. While the number of publications in CHI is consistent with the size of the conference and predominance in the field, the fact that the other most included conferences are ISMAR and VR indicates that asymmetric collaboration has mainly been cited in the context of systems involving mixed reality.

Keywords: This is confirmed when looking at the authors’ keywords associated to each article, which reveal a predominance of words referring to mixed/augmented/virtual reality/3D systems (27% of all the keywords). In comparison, words referring to collaboration, explicitly mentioned in our query, represent 15% of all the keywords. In contrast, keywords referring to asymmetry represent only 4% of all the keywords. The other keywords refer to either the applications, the technologies or the methods.

Terms used for asymmetry: There are nine different terms used to refer to asymmetric collaboration in the reviewed papers. The most common term (found in 28 papers) is “different”. The second most used term (found in 27 papers) is “asymmetry” (or its derived terms such as “asymmetric” or “asymmetrical”). Seven other terms are each used in 8 papers or less (see Figure 2-right).

4.2 Systems Properties

In this section, we present the main properties of the 57 systems presented in the 46 papers of our corpus.

Remote vs Co-located: Most of the asymmetric systems are used in remote collaboration (47 systems). The other asymmetric systems involve a collocated collaboration (10 systems).

Number of locations: most of the studied systems involve only two locations (41 systems) or one location in collocated cases (10 systems). Only 6 systems presented in 4 different papers involve more than two sites.

Number of interaction spaces: Most of the studied systems involve two interaction spaces (51 systems), with only 2 systems involving three different interaction spaces, and 4 systems more than three. When three or more interaction spaces are present, some may be identical (e.g., one user using a desktop while two others use a VR setup).

Number of users: Most of the systems are studied with one user in each interaction space (49 systems), while 8 systems involve interaction spaces with more than one user (5 systems involve exactly 2 users in one interaction space, and 3 systems can have multiple users in one interaction space).

Interaction devices: We found 226 input devices that can be classified into 22 different types. The most common categories are cameras (36/226), microphones (32/226), VR controllers (29/226) and mice (23/226). We found 294 input languages classified into 14 categories. The most common categories are *position* (68/294), *video* (40/294), *orientation* (41/294), *click* (37/294) and *gestures* (37/294).

We also found 163 output devices that we classified into 14 different types. The most common are VR head-mounted displays (35/163), monitors (31/163) and AR optical see-through head-mounted displays (26/163). We found 186 output languages classified into 5 categories. The most common are *graphics* (113/186) and *video* (45/186). Interestingly, only one paper [26] does not have “graphics” or “video” as an output language in one of their space and uses only the *voice* output language.

XR vs Not-XR: We found that 46 out of the 56 systems involve XR technologies (i.e. AR or VR), even though our approach was domain agnostic. This could reflect the recent increase in XR-related research or a higher interest in asymmetric interaction within this domain.

5 Dimensions of asymmetric collaborative interaction

In this section, we report on the analysis and coding that led to our characterization of asymmetric collaborative interaction. After detailing the analysis process, we describe each of the eight dimensions of our framework.

5.1 Overview of the analysis process

As described in section 2.3, four researchers conducted this analysis. The corpus of papers was distributed across them, to identify the asymmetries within each system, given the system properties presented earlier, as well as the description of the asymmetry. We started with a first list of asymmetries, defined from our analysis of previous work: **content access**, related to the role [3, 18]; **dimensionality**, related to the level of the reality-virtuality continuum [76]; **input and output devices** and interaction languages, related to the user capabilities [18]; the **display layout**, given the variety

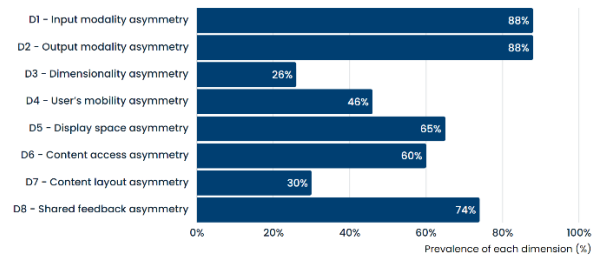


Figure 3: Prevalence of each dimension of asymmetry in our SLR systems.

of device configurations in cross-device systems [9]; finally, the **shared feedback**, related to the mutual awareness [3].

We conducted a first iteration using these codes on a subset of the corpus, with the instruction to add more dimensions if other asymmetries were found in the systems or papers. After this first coding, the researchers met to discuss the dimensions. We decided to add two more asymmetries: **user mobility** and **display space**. We also decided to split the shared feedback into four sub-categories: **view-point sharing**, **user representation**, **environment sharing** and **shared interaction feedback**. Finally, we coded all papers using this final set of asymmetries. The prevalence of each asymmetry is shown in Figure 3.

5.2 D1: Input modality asymmetry

Definition: Given the seminal definition of an interaction modality as the couple <device, language> [58] (e.g. <mouse, position>), **we considered an input modality asymmetry whenever the device or the interaction language was different across spaces, or if a device or language was absent from one of the spaces**. While input asymmetry has already been considered in prior models and frameworks (see our background section), it is usually examined from a device-only perspective ([2, 7, 85]).

Prevalence: We found input device asymmetries in 88% of the systems (50/57), and input language asymmetries in 61% of the systems (35/57), see Figure 4. Regarding the input device asymmetries, 44% involved a mouse, 42% a camera, 38% a VR controller, 36% a VR head-worn sensor, 22% an AR head-worn sensor, 22% a depth camera, 20% a hand/body tracking device, and 14% a keyboard. Regarding the interaction language asymmetries, 60% involved video, 49% involved position, 46% involved clicks, 37% involved the use of gestures, and 23% involved touch.

Illustrative examples and impact on collaboration: In the system developed by Kim et al. [44], an expert using a mouse on a desktop environment helps a collaborator who shares his workspace and actions with a handheld camera (Figure 5-left). The mouse was used for pointing and drawing annotations: results showed that the pointer and annotations increased the feeling of connectedness and being together compared to having only video conference. Input asymmetry can also happen in co-located environments: Müller et al. [56] studied a co-located interaction where each user could choose between a mouse or a tabletop touchscreen (Figure 5-right). They demonstrated that pairs where one participant used touch and the other used a mouse did not restrict their interaction to distinct

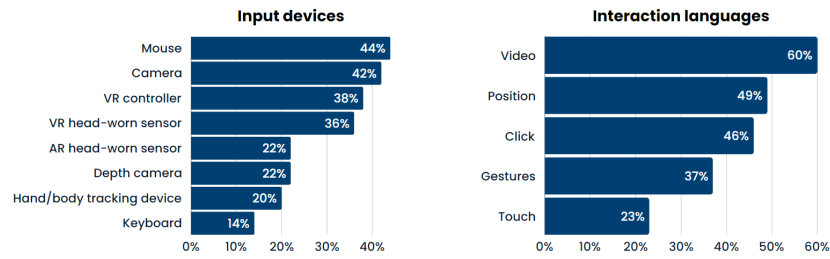


Figure 4: Prevalence of the most common input devices (left) and interaction languages (right) involved in input modality asymmetries.

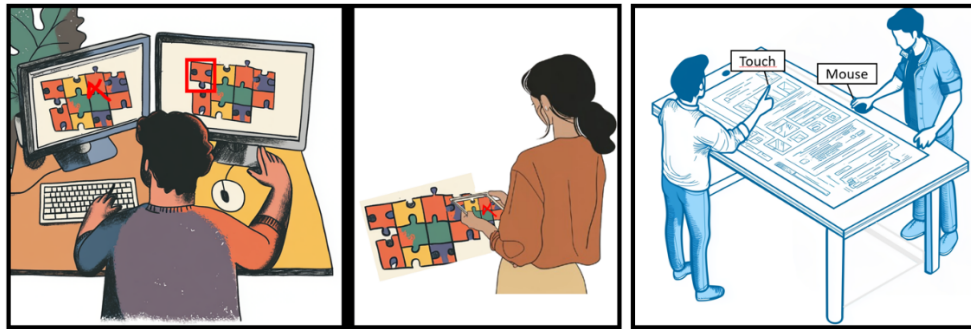


Figure 5: Examples of asymmetric input modalities: left: desktop vs. mobile input in remote collaboration [44], right: mouse vs. touch in a co-located collaboration [56].

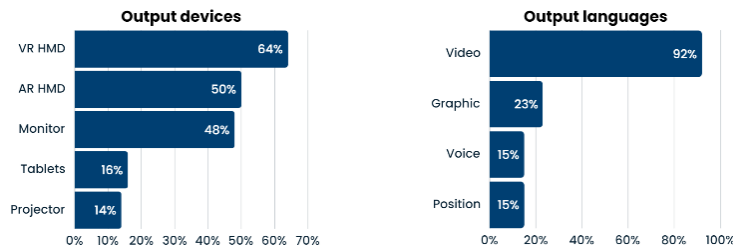


Figure 6: Prevalence of the most common output devices (left) and interaction languages (right) involved in output modality asymmetries.

areas on the tabletop, unlike pairs where both participants used touch.

5.3 D2: Output modality asymmetry

Definition: Similar to the input modalities, we consider an output modality as the couple <output device, output language> [58]. **We followed the same rules as for input modalities to declare an output modality asymmetry.** Similarly to input, output asymmetry is usually examined from a device-only perspective ([2, 7, 85]) in prior models.

Prevalence: We found asymmetries in output devices in 88% of the systems (50/57), and in output languages in 23% of the systems (13/57), see Figure 6. These results are coherent with the input asymmetries, which showed a large variety of display devices. However,

these displays share a graphic language, hence limiting the number of output language asymmetries.

More precisely, 64% of the output device asymmetries involved a VR head-mounted display (HMD), 50% an AR HMD and 48% a monitor. The three of them were most often opposed to one of the other two. Less frequent, tablets participate in 16% of the asymmetries, and projectors in 14%.

Regarding output language asymmetries, almost all of the asymmetries involved video (92%). For the other output languages, 3 asymmetries involved graphics, 2 involved voice and 2 involved movement of physical objects.

Illustrative examples and impact on collaboration: Grandi explored different combinations of symmetric and asymmetric VR and AR [22]: among them, an asymmetric condition involving a



Figure 7: Two illustrative examples of output modality asymmetries: left: VR headset vs. tablet [22], right: projector vs. speakers [26].

VR HMD and an AR tablet (Figure 7–left). They showed that the symmetric VR-VR outperformed the asymmetric VR-AR and users reported lower mutual assistance in the asymmetric setup. Gugenheimer et al. investigated different assistive technologies to support deaf individuals in face-to-face interactions with hearing people [26]. In one of those systems, the hearing participant’s words were translated live into sign language and then projected onto the upper body of the hearing participant. The deaf participant could respond in sign language, which was translated into spoken language and played through speakers (Figure 7–right). In this case, the output modality asymmetry had a different effect on the two users: the hearing participant’s movement was restricted, which was not the case of the deaf participant.

5.4 D3: Dimensionality asymmetry

Definition: The dimensionality refers to the number of dimensions of the interactive system, both in input and output, considering both the device and the language. For instance, a desktop user may employ a 3D joystick and see a 3D environment, while another desktop user employs a 2D mouse; a gesture can be performed on a surface (2D) or in the air (3D); a video can be displayed on a screen (2D) or be immersive (3D); a sound can be displayed spatialized or not, etc. To account for these types of asymmetries, we used the concept of dimensionality, defined as the number of dimensions of the user’s interaction. **There is an asymmetry of dimensionality when the number of dimensions of the modalities differs across spaces.** This dimension is seldom explicitly considered in prior models. For instance, Schafer et al. [75] consider different interactive tasks, such as mid-air drawing in 3D and 2D drawing, but do not mention dimensionality as a property.

Prevalence: We found dimensionality asymmetries in 26% of the systems (15/57), see Figure 8. More precisely, we found dimensionality asymmetries in input modalities in 16% of the systems (9/57). The most often involved input modalities are 3D VR controllers (6 systems) and 2D mice (6 systems). We found dimensionality asymmetries in output modalities in 19% of the systems (11/57). Most often, this asymmetry involved 3D VR/AR displays against 2D screens (9 systems).

Illustrative examples and impact on collaboration: On SharedNeRF [72], a local user manipulates a 3D scene, while the remote user can only interact using the 2D mouse (Figure 9–left). In one of their discussions, they emphasized that using a 2D interface for the remote user, which required manually adjusting the camera

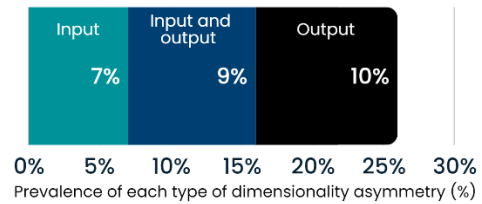


Figure 8: Prevalence of the dimensionality asymmetries.

view, was cognitively demanding. They suggested that a 3D output device allowing the user to intuitively change their perspective by simply moving their head, like a VR headset, presented a promising avenue for further exploration. Medeiros et al. [54] investigated using VR to provide one of the collaborators with 3D visualizations in a tactical resource planning scenario, while the other works on a desktop (Figure 9–right). Their study suggests that tasks such as collaboratively analyzing the topology of geographical data can lead to a more comprehensive and intuitive understanding of the terrain when performed in VR. However, for tasks requiring an overview of a large geographical area, it was more effective to continue using a desktop interface.

5.5 D4: User’s mobility asymmetry

Definition: Mobility describes the capability or necessity of a user to move while having access to the interaction devices. For instance, a user wearing an AR HMD can move in space. We consider an asymmetry in mobility if it is different across users. This asymmetry can be partially found in prior models: Assaf et al. [3] consider the “User Position” situation, which refers to users movement limits and placement; Brudy et al. [9] consider the dynamics of devices within a cross-device environment.

Prevalence: We found asymmetries in user’s mobility on 46% of the systems (26/57), see Figure 10. Most often, this asymmetry involves a user sitting in front of a desktop environment collaborating with a moving user (19 systems). In general, this moving collaborator wears a VR HMD (6 systems) or an AR HMD (6 systems), or holds a tablet (2 systems). There are situations where a desktop user collaborates with multiple users moving in a room (2 systems), with users moving around their personal workspace (2 systems) or with a user moving in front of a wall display (1 system).



Figure 9: Illustrations of the dimensionality asymmetry: on the left, the local collaborator manipulates a set of 3D physical objects, while the remote collaborator performs 2D interaction on a video showing the remote set of objects [72]. On the right, VR is used to provide one of the collaborators with 3D visualizations in a tactical resource planning scenario [54], images used with the permission of VRVis GmbH and IMG - Österreichisches Bundesheer.

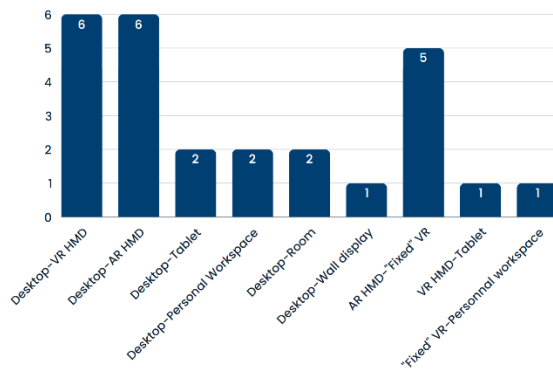


Figure 10: Number of systems with a user’s mobility asymmetry, according to the types of devices involved.

Illustrative examples and impact on collaboration: In Reticular Spaces [5], local users can move in a smart room equipped with wall displays, tabletops and tablets (Figure 11-left), while remote users can virtually join from their desktop environment. The authors noted that mobility was valued by local users, as it enabled them to easily switch between tasks by changing devices or sharing one. Additionally, being able to see which device someone was using provided others with more insight into their current activity. However, this level of awareness was not available about remote users. Prouzeau et al. [67] explored a collaborative situation where one user is sitting in front of a desktop computer (Figure 11-right), while the other is moving to interact with a wall display, both in the same location. Their paper suggests that because of this asymmetry of mobility, it was not possible to provide the same type of shared feedback to all the users.

5.6 D5: Display space asymmetry

Definition: There is a display space asymmetry when one interaction space has significantly more space to display content than another interaction space. To classify the display space, we considered three levels: small (mobile and wearable displays), medium (desktop screens, AR HMDs) and large (tabletops, wall displays, VR HMDs, multi-display setups). This dimension is partially reflected in the “scale” characteristic within the cross-device taxonomy proposed by Brudy et al. [9] and in the differentiation between “large displays”

and other types of displays highlighted both in their work and other studies such as [2].

Prevalence: We found display space asymmetries in 65% of the systems (37/57), see Figure 12. As said earlier, one of the most frequent situations is an asymmetry between medium AR and large VR displays, which significantly differ in their field of view (FoV) size (15 systems). Another frequent situation involves a large VR display and a medium desktop (8 systems). Such asymmetry was also often found when using a tablet on one side and a monitor (2 systems), VR HMD (2 systems) or tabletop (1 system) on the other side. Multi-display systems are also presenting this asymmetry (2 systems).

Illustrative examples and impact on collaboration: Tong et al. [84] introduced a VR-PC system to interact with a graph and documents (Figure 13-left). They compared a symmetric PC-PC with the asymmetric VR-PC, and showed that PC users perceived less mental load and effort in the latter, as VR users could view all documents and graphs at the same time, hence improving collaboration. In the TransceiVR system [83], a tablet user can annotate images mirrored from a VR collaborator’s view (Figure 13-right). Despite the difference in display size, the results showed that the system allowed users to complete the task faster and made communication easy and efficient.

5.7 D6: Content access asymmetry

Definition: There is a content access asymmetry in two cases: first, when some content involved in the task is not visible for some collaborators; second, when everyone can view the content, but only some collaborators can act on it. Prior models have usually considered either the first or second case. For instance, Ouvre-son et al. [63] proposed the Balance of power dimension, which refers to group members having different degrees of control over information.

Prevalence: In our SLR, 39% of the systems (22/57) are concerned by the first case, with a partial sharing of the content of the task between users. The second case concerns 21% of the systems (12/57) where the content of the task is totally shared between users, but only some users can act on it. In total, 60% of the systems (34/57) present a content access asymmetry (see Figure 14-left).

Illustrative examples and impact on collaboration: Drey et al. [17] developed a collaborative learning system where both teachers and learners can view a virtual forest environment and animals (Figure



Figure 11: Examples of asymmetric user's mobility: multiple local users can move in a room [5], or in front of a wall [67], while other collaborators join from their static desktop environment.

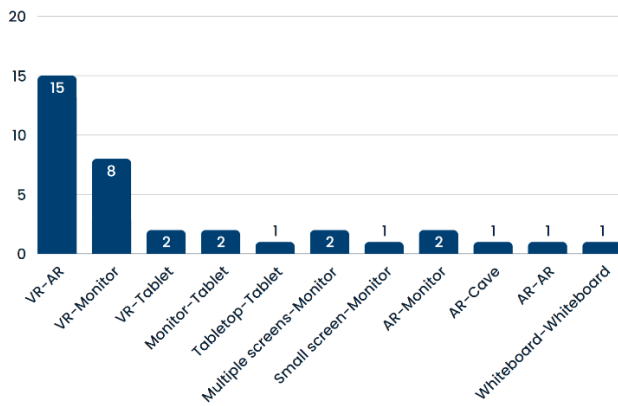


Figure 12: Number of systems with a display space asymmetry, according to the types of devices involved.

14–center). The student used a VR headset, while the teacher accessed a spectator view on a tablet, without the ability to move or interact within the virtual space. This design aimed to reduce the teacher's cognitive load, allowing them to focus on the student's actions. However, a study showed that compared to a fully symmetric system, this setup resulted in reduced workspace awareness, increased miscommunication, and a higher cognitive load. O'Neill et al. [62] designed a system supporting collaborative troubleshooting of office copiers and printers between a customer and a remote troubleshooter (Figure 14-right). There is an asymmetry in content access: the customer can see and act on the real device, while the troubleshooter sees a 3D model of the device and additional information (such as the origin of the problems or instructions to solve them). In their study, they found that this asymmetry results in confusion when the status or model is not correctly updated after a customer's action, and that troubleshooters and customers may disagree on which action to take first due to how the information is presented.

5.8 D7: Content layout asymmetry

Definition: We analyzed the arrangement of virtual or physical displays in each interaction space. We identify a content layout asymmetry if the arrangement of displays (side by side, separated) or their orientation (vertical, horizontal) differs across interaction

spaces. This dimension is rarely expressed in prior models. The closest concept is the “configuration” dimension proposed by Brudy et al. [9], which classifies the spatial or logical distribution of UIs in a cross-device environment.

Prevalence: We found content layout asymmetries in 30% of the systems (17/57), see Figure 15. Most often the asymmetry was due to the difference between a VR layout and a desktop layout (6 systems), or between a desktop layout and layouts involving horizontal displays (6 systems). Two papers addressed the case of layout asymmetry due to differences in the position of physical fixed devices. Interestingly we only found one asymmetry between AR and VR layouts, involving a difference in scales.

Illustrative examples and impact on collaboration: Saffo et al. [71] addressed the question of how desktop and VR users can collaborate when presented with different views or layouts of the same data (as illustrated in Figure 16-left). They showed that the user with the layout best suited for a particular task would often take charge. They also showed that such asymmetric layouts need good information cues to support references and deixis. Fink et al. [19] proposed the concept of *Re-locations* to simulate collocation around physical devices in remote collaboration despite physical differences across the involved remote display layouts (Figure 16-right). This allows to benefit from collocated advantages for collaboration such as spatial and workspace awareness and physical referencing.

5.9 D8: Shared feedback asymmetry

Definition: As said earlier, we decided to code four aspects for the shared feedback asymmetry (Figure 17): First, whether the environment sharing was asymmetrical, i.e. if users did not have the same view of each other's environment; Second, whether the user representation differed across spaces; Third, whether the viewpoint sharing was asymmetrical (not shared, partially shared, or totally shared); Finally, whether the interaction feedback was different across spaces. These four aspects are frequently considered in the literature either individually or partially grouped, with different levels of granularity. For example, Assaf et al. [3] considered “environments” and “point of view”, and detailed different types of visual cues describing the user representation.

Prevalence: We found asymmetries in shared environment in 56% of the systems (32/57). In all of them, only one of the collaborators shared his environment. We did not encounter the case where two

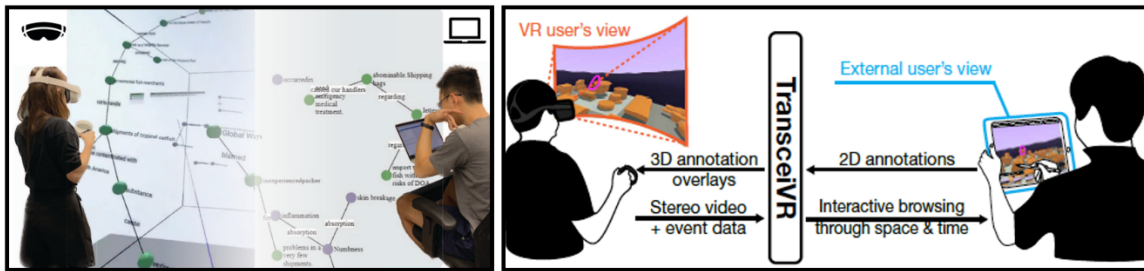


Figure 13: On the left, an example of a VR-PC asymmetrical display space with a shared graph and documents [84]. On the right, a user with a small tablet display annotates images from the VR user’s view [83].

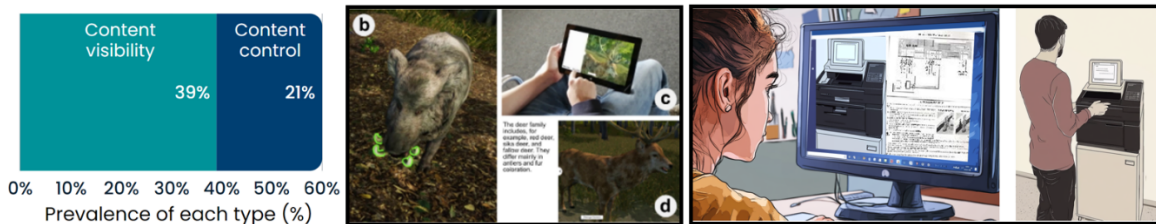


Figure 14: On the left: prevalence of the content access asymmetries. On the right: illustrative examples of asymmetrical content access: first, a collaborative learning system where the teacher has different content than the learner [17]; second, a collaborative troubleshooting system where only the customer can act on the printer and the troubleshooter has access to more information [62].

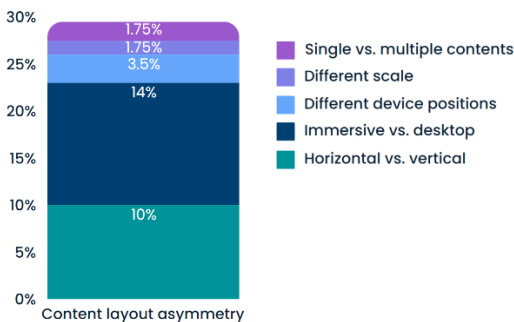


Figure 15: Prevalence of the content layout asymmetry.

environments are shared during a task, hence where environments are shared in different ways.

We found asymmetries in user representation in 37% of the systems (21/57). In 10 systems, only the users from one space are represented, either by an avatar (4 systems), by virtual hands (1 system) or appearing in a video (5 systems). In 10 other systems, the aspect of the user representation differed between spaces: either different avatars (3 systems), or avatars vs. 2D videos (2 systems), 360 videos (4 systems) or 3D videos (1 system). Finally, in one system with three users, one is not represented and the last two are represented by two different types of avatars.

We found asymmetries in viewpoint sharing in 32% of the systems (18/57). Most often, only one viewpoint is shared (12 systems).

There are also cases where one viewpoint is totally shared while the other viewpoint is partially shared (6 systems).

Finally, we found shared feedback asymmetries in 47% of the systems (27/57). These mostly correspond to only one only sharing annotations (9 systems) or visual cues (6 systems). In the other cases, the differences between shared feedbacks were specific to the system.

Illustrative examples and impact on collaboration:

Regarding user environments, Teo et al. [82] compare sharing a local user environment with either a 360 camera or a 3D scene reconstruction, with a remote VR collaborator (Figure 18-left). They found that participants performed significantly better on collaborative search tasks in the 360° environment and experienced a greater sense of social presence.

Regarding user representations, Yoon et al. [90] studied the effect of avatar appearance on social presence during remote collaboration (Figure 18-right). They found that a whole-body avatar increases the social presence, and that the style of avatar has to be chosen depending on the type of collaboration (e.g. professional meeting or entertainment).

Regarding viewpoint sharing, Johnson et al. [39] explored different ways for a remote helper to provide spatial information to a local worker. Only the local worker shares a first-person view (Figure 19-left). The results show that guidance reduces the need for spatial information, and makes expertise more accessible without requiring remote experts to be in immersive environments.

Regarding interaction feedback asymmetries, Kim et al. [43] evaluated the effect of different communication cues for Mixed Reality remote collaboration between an expert and a local worker

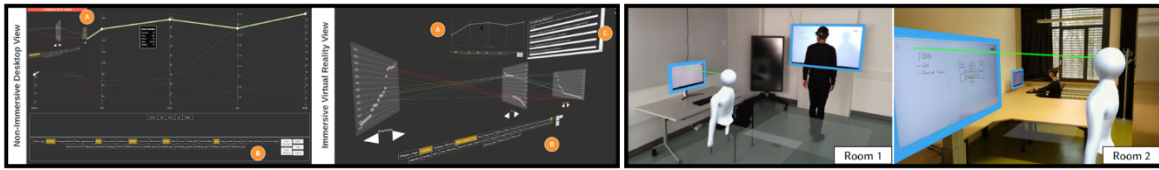


Figure 16: Illustrations of a content layout asymmetry. Left: the VRxD system presents different layouts between the desktop user (left) and the VR user (right) [71]. Right: different layouts of displays between remote collaborators [19].

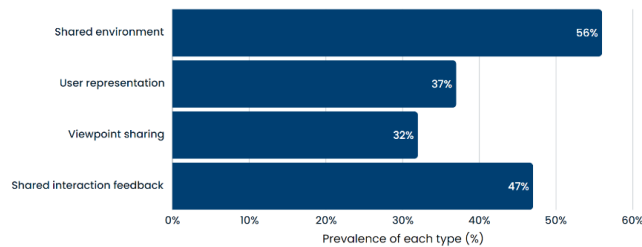


Figure 17: Prevalence of each type of shared feedback asymmetry.

(Figure 19-right). They found that having a sketch cue in addition to hand gestures is better than hand gestures only, but the addition of a pointer did not have a beneficial effect.

6 Discussion

In this section, we first examine how asymmetries are perceived in the literature on collaborative systems. We then introduce a set of 8 open challenges and opportunities in the field of asymmetric collaborative systems revealed by our literature review. Finally, we discuss the limitations of our work and its perspectives.

6.1 Are asymmetries undesirable?

Historically, interaction asymmetries have often been presented as an undesirable property or design challenge to overcome in collaborative systems. For instance, back in 1998, Benford et al. [6] noted that asymmetrical awareness between a physical and virtual environment made communication problematic. As such, research on collaborative systems either tended to focus on supporting symmetries (leading to the acronym WYSIWIS, “What you see is what I see”, describing the predominant symmetric form of interaction [80]) or on providing solutions for asymmetries. In our SLR, 52% of the papers (24/46) present asymmetry as an initial constraint, usually due to the different contexts or roles of the users (e.g. remote expert). For instance, Fink et al. [19] address the problems of incongruent workspaces for synchronous remote collaboration with AR.

The 48% remaining papers of our SLR (22/46) present the asymmetry as a design opportunity or a valuable asset. For instance, Grandi et al. [22] note that “context of CVEs, asymmetry represents the capacity of individuals in a group to have different means to visualize and interact with virtual content”. Other previous work has already pointed out that asymmetry is naturally present in social interaction [63] and can even be sometimes beneficial to a

shared task. For instance, Volda et al. [86] argued the value of asymmetry in media spaces, e.g. the asymmetry of engagement in blogging, or the asymmetry of place in social networking. Harris et al. [29] designed asymmetric games to leverage differences between players and improve multiplayer engagement.

There are nuances to this dichotomic vision of asymmetries. For instance, most works that initially present asymmetry as a constraint, transform it into a design opportunity, which can be resolved by developing other forms of asymmetry (for instance equipping the remote expert with AR technologies).

6.2 Challenges and opportunities of asymmetric collaboration systems

The asymmetries identified in this SLR also raise new challenges for the design of asymmetric collaboration systems. In this section, we report on the challenges raised in the most recent papers of our SLR (i.e. less than 2 years old) and relate them to the asymmetries introduced above:

Exploiting each space’s unique interaction capabilities (Chlg1): Our SLR revealed the high frequency of **input and output modality asymmetries** (88% of the reviewed papers each). As the different interaction spaces offer various interaction modalities, it is important to consider how to best exploit each of them for the collaborative task. Tong et al. [84] noted that participants wished to customize the input on the PC, and regretted that the VR system design did not use all the benefits of VR embodied interaction. Hence, properly exploiting and optimizing the capabilities of each space interaction modalities is crucial to unleash the potential of asymmetric interaction. This could be addressed by using context-aware techniques [49], where the interaction would adapt to the modalities at hand, or through dynamically reconfigurable interfaces, which can be configured by the user using constraint-based approaches [59].

Resolution of the shared environment (Chlg2): The **shared feedback asymmetries** related to environment sharing (56% of the systems) show that the capture and rendering of the environment is greatly influenced by the technologies used. In particular, sharing the user environment through 360° videos or depth cameras poses challenges regarding the level of fidelity of the rendering on each interaction space [92]. A low-fidelity rendering has been shown to have an impact on the spatial understanding of collaborators [40]. To address this challenge, Yu et al. [91] suggest adding HDR cameras to compensate for the differences in illumination. Recent advances such as volumetric NeRF representations are promising to enhance the high-fidelity sharing of physical environments or objects [72]. However, rendering such representations with a high visual fidelity in real-time is still an open challenge. Other solutions

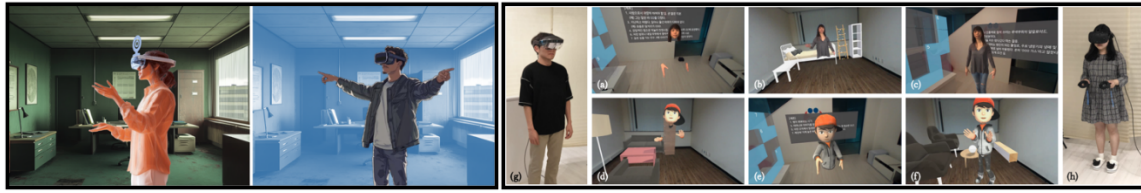


Figure 18: Illustrative example of asymmetric shared feedbacks: asymmetric environment sharing on the left [82] and a study of different user's representations on the right [90].

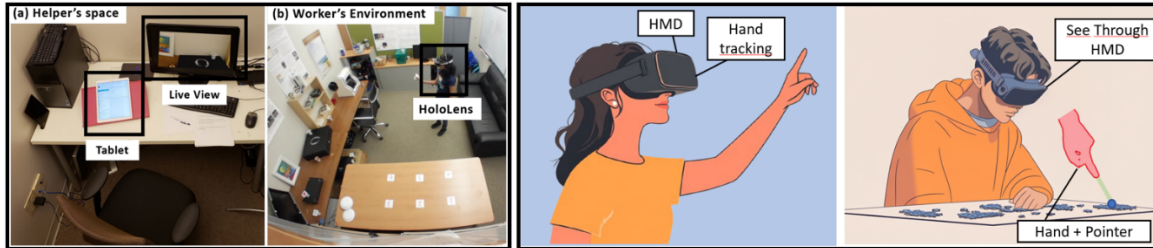


Figure 19: Illustrative example of asymmetric shared feedbacks: asymmetric viewpoint sharing on the left [39] and on the right an asymmetric interaction feedback with visual cues only provided by one user [43].

could include using a dynamic level of detail (LoD) [89], which can provide high-resolution visuals for participants only when needed, or multi-layered representations where users can access the appropriate resolution [50].

Control over shared viewpoints (Chlg3): We found **shared feedback asymmetry** related to viewpoint sharing in 32% of the systems of our SLR. Sakahista et al. [72] underlined that allowing remote users to change their view on the collaborator's scene can improve communication, by, for instance, leveraging hand gestures or annotations, but takes valuable cognitive resources. Finding seamless interaction solutions to provide control over the shared viewpoints while limiting the cognitive efforts remains an open design challenge. Other perspectives include adopting multi-viewpoint modes [81], where users can see multiple viewpoints at the same time, or viewpoint synchronization methods [93], which enable participants to sync their viewpoints with others at any time.

Level of fidelity of the user representation (Chlg4): The part of **shared feedback asymmetry** focusing on user representation (37% of the systems) revealed a high variability of the representation. While the question of the correct level of fidelity of avatars has been the subject of several works, it is still an open challenge, as it is highly dependent on the context and task. For instance, Yu et al. [91] noted that in the context of medical teleoperation, a realistic avatar was less relevant for task completion as participants did not pay attention to it, since they were focused on the medical task. Ihara et al. [32] proposed augmenting holographic telepresence with mobile robots and showed that it increases co-presence compared to having only the avatar, but noted that other robot form factors could be explored. Perspectives to address this challenge could include adapting the level of fidelity based on collaboration dynamics [53], for instance, by providing a high level of fidelity when in close proximity but reducing the level of fidelity in large

collaborative scenarios. Another idea could be to exploit the multi-modal representation of the avatar, by adjusting the level of fidelity of the visual representation independently from other modalities, such as voice or haptics [94].

Understanding the other collaborators' interaction space (Chlg5): Given the variability of devices used and the distribution of the information on them, described above as a **content layout asymmetry** (30%), collaborators may be facing totally different working spaces, which impacts spatial awareness and social presence [19]. Smoothly supporting this diversity would both contribute to take advantage of each interaction space capabilities and foster a better mutual understanding of the different interaction spaces involved. World-in-miniature metaphors representing the remote collaborator's space could prove valuable to this end [14]. Another perspective on this challenge would be to remove the differences across spaces, as in Re-locations [19], which aligns the incongruent spaces by locally relocating the remote user representation.

Other remaining challenges related to the asymmetries are orthogonal to our dimensions:

Scalability (Chlg5): As underlined by Zaman et al. [92], having a large number of collaborators in asymmetric situations poses multiple challenges, such as the optimal positioning of their avatars, or providing contextual information about their location and movement with limited bandwidth to minimize latency. Besides, previous work mostly considers situations with a limited number of input and output devices, or simple spatial setups [24]: it is still unclear how some of the previous research will scale to more complex real-world situations. Massive Multiplayer Online Role-Playing Games (MMORPGs) represent an interesting use case for exploring this challenge. AI technologies can play a pivotal role in optimizing, scaling or adapting interactions in such contexts.

Asymmetric workload (Chlg6): While previous work has shown that asymmetric collaboration can be as effective as symmetric

Table 1: Analysis of the presence of our dimensions of asymmetric interaction in previous models of collaboration. The second column specifies if the referred model considers the concept of asymmetry or not.

	Considers asymmetry	Input Modality	Output Modality	Dimensionality	User's Mobility	Display Space	Content Access	Content Layout	Shared Feedback
[7] Billingham 1999	Yes	X	X				X		X
[2] Ashdown 2007	Yes	X	X		X	X	X	X	
[86] Voda 2008	Yes		X						X
[63] Ouverson 2021	Yes	X	X				X		X
[68] Radu 2021	Yes	X					X		X
[3] Assaf 2024	Yes						X		X
[75] Schäfer 2022	Yes	X	X						X
[18] Ens 2019	Yes	X	X						X
[23] Grasset 2005	No						X		X
[85] Van der Meer 2023	No	X	X				X		X
[52] Mateescu 2021	No	X							X
[9] Brudy 2019	No				X	X		X	
[51] Lopez 2017	No	X	X				X		X
[21] Ghamandi 2023	No								X

collaboration [84], the cognitive load of each collaborator can highly differ. In their system, Tong et al. [84] noted that while the mental demand and effort of PC users were low, VR users felt frustration and physical fatigue, hence resulting in an asymmetric workload, which could affect collaboration quality. Anticipating and reducing this asymmetric workload is an open challenge. Addressing this challenge will first require adopting the most appropriate workload measure according to the user context [46]. This measure could then be used to feed dynamic workload adjustment techniques to redistribute the tasks across collaborators based on their workload.

Longitudinal studies on asymmetric collaboration (Chlg7): Almost all of the papers in our SLR conducted controlled in-lab experiments. Saffo et al. [71] point out that conducting longitudinal studies of asymmetric collaborative systems is needed to evaluate the impact and behaviour changes during long-term and domain-specific tasks. While such longitudinal studies have been conducted on more traditional hybrid meetings (see section 6.4 below), it is challenging to conduct such studies on heterogeneous systems because they are not yet widespread, limiting the availability of users over extended periods.

6.3 Comparison of our dimensions to prior models

As mentioned in our background section, several models have been proposed to characterize collaborative systems and asymmetric

collaboration. In Table 1, we present a comparison of these models with the one introduced in this paper, highlighting both the overlapping dimensions and the key differences.

We can observe that the dimensions of input modality, output modality, content access and shared feedback are referred to in several works. However, these works usually consider only a sub-part of our dimension definitions, as explained in the previous sections. Besides, input and output modalities are rarely considered separately.

More importantly, our interaction-centric analysis of collaborative systems revealed dimensions that are rarely addressed in prior work, such as dimensionality, user mobility, display space and content layout. These asymmetries are likely difficult to identify without carefully describing the devices that make up the various interaction spaces. In particular, the “dimensionality” is not referred to as an explicit attribute in prior models.

Overall, none of the existing models in the literature provide a set of attributes that fully encompass all our dimensions. We believe this is due to our original approach of analyzing asymmetric interaction from a system perspective, as opposed to prior work. We further discuss this aspect in the next section.

6.4 Scope of the SLR

The previous challenges and opportunities have been underlined in our SLR papers. As said before, our corpus of paper is predominantly composed of XR systems. This can be attributed to our goal

of studying functional systems and focusing on their properties (e.g. interaction, feedback, etc.). Indeed, recent technological advances in mixed reality have paved the way for innovative and promising support for collaborative activities, thereby increasing the amount of research exploring their impact on such activities. Meanwhile, our study and contributions are novel, as no previous works have systematically studied the properties of asymmetrical interaction in collaborative systems, as illustrated earlier in Table 1.

Our work is complementary to other approaches that have taken an ethnographic or design perspective: instead of proposing novel interactive systems or prototypes as the papers in our SLR, these previous studies investigated hybrid collaborative situations in more traditional collaborative systems, i.e. videoconference-based or cloud-based. Their findings can, however, be linked to the dimensions of our model. For instance, Chang et al. [13] observed that videoconferencing on mobile devices affects user-perceived streaming quality (*Chlg2: Resolution of the shared environment*). Salaberry et al. [73] recently studied asymmetrical access to social cues on video-conferencing (either audio only or audio and video): they found that in asymmetric interaction, participants who send more cues than they receive rate the interaction as feeling more present/connected than the other participants (*Chlg4: Level of fidelity of the user representation*).

Busboom et al. [10] showed that asymmetrical experiences in hybrid collaboration introduce what they call “compensation work” (*Chlg6: Asymmetric workload*). Similarly, Bjorn et al. [8] investigated whether cooperative work in hybrid work contexts could be symmetric. They concluded that asymmetric interactions are unavoidable in today’s synchronous collaboration activities, and can have important social impacts, such as the risk of exclusion in hybrid work. They identified three design challenges: 1) reducing the effort of articulation work required to bound artifacts-ecologies (*Chlg6: Asymmetric workload*); 2) compensating for audio, visual and other non-verbal asymmetries (*Chlg1: Exploiting each space’s unique interaction capabilities*); and 3) enabling participants in the emotional labour of relation work.

Overall, these prior studies demonstrate that many of the challenges identified in our SLR are common to other types of systems beyond the realms of XR and heterogeneous systems.

6.5 Limitations

Our work is limited by the scope of our SLR. First, our SLR included only papers that focused on “asymmetry” (or similar terms). The rationale for this choice was to analyze previous works where the asymmetry was a central aspect, hence include some results or discussion on its characteristics or impact on collaboration. However, it is obvious that multiple other collaborative systems presented in the literature include some type of asymmetry, and could also be categorized using our dimensions. Performing a full-scale analysis of the literature on collaborative systems was out of the scope of our work, but could be done in the future (see the Perspectives section).

A second limitation regarding the scope is that most of our papers present heterogeneous systems. During our inclusion/exclusion process, we discarded papers presenting web-based systems, some of them focusing on responsive design where users interact through

either a desktop computer or a mobile device. We believed this type of asymmetry is very frequent and less interesting, and that it would lead to coding a large number of papers focusing solely on this aspect of web-based interfaces.

Third, our paper considered mostly synchronous collaboration. Hence, while the location aspect is present in our asymmetries, the temporal aspect is not. Including asymmetries over time is an interesting perspective to extend our work and analyze systems focusing on asynchronous collaboration.

A final limitation of our systematic literature review concerns the lack of control over the underlying search algorithm of the ACM DL or IEEE Library. In retrospect, we were surprised that some of the papers added by the experts had not been found initially by these search engines. Unfortunately, there is not much we can do about this issue. We believe that sharing our queries and detailing our screening process will improve the reproducibility of our work. We also plan to iteratively add any new relevant papers that would come to our attention.

6.6 Perspectives

Our paper presents a set of dimensions that can be used by practitioners to classify their work, or find related papers for a given asymmetry, looking for previous solutions or experimental results. To increase the impact of our work, it would be interesting to develop a web tool that 1) could allow practitioners to register and classify their systems using our dimensions, 2) find papers related to a given asymmetry, and 3) keep an updated view of the prevalence of asymmetries in collaborative systems. We plan to develop this platform in the near future and include papers that were not part of our SLR as they did not focus on asymmetric interaction. A stripped-down version of the toolkit is published on a website at the following address: <https://asymmetric-interaction-in-collaborative-system.fandom.com>.

Our paper also opens the avenue for a systematic experimental exploration of the different dimensions of asymmetry. Our work can help in guiding research questions on asymmetric interaction and designing experiments based on our identified properties. For instance, content layout asymmetry is one of the less explored dimensions in our review and merits further attention.

7 Conclusion

In this paper, we reported on a systematic literature review (SLR) on asymmetric interaction in collaborative systems. We analyzed 57 systems presented in 46 papers by coding the collaborative tasks, interaction spaces, input and output modalities, as well as their shared feedback. From this analysis and through iterative coding, we were able to identify 8 dimensions of asymmetry: input modality, output modality, dimensionality, mobility, display space, content access, content layout and shared feedback. For each of these dimensions, we provide a definition, report on their prevalence in our corpus and present illustrative scenarios which highlight the impact of these dimensions on collaboration. Finally, we discuss the current understanding of asymmetric interaction, as well as future challenges and opportunities.

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All figures were used with the authors' permission, except for Figures 5-left, 5-right, 14-right, 18-left and 19-right, which were generated using MidJourney to replicate the systems described in the literature.

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A APPENDICES

Table 2: For each type of asymmetry, list of the papers in our SLR presenting an asymmetric system of that type.

D1: Input modality asymmetry	[Bai 20] [Bardram 12] [Billinghurst 99] [Cavallo 19] [Dey 17] [Drey 22] [Gasques 21] [Grandi 19] [Gugenheimer 17] [Gugenheimer 17] [Ihara 23] [Irawati 08] [Jing 22] [Johnson 21] [Johnson 23] [Jones 2021] [Kim 14] [Kim 19] [Lee 18] [Medeiros 22] [Morishima 12] [Muller 08] [Norman 19] [Numan 22] [O’Neill 11] [Piumsomboon 18] [Piumsomboon 19] [Prouzeau 18] [Reilly 10] [Saffo 23] [Sakashita 24] [Teo 19] [Thovari 20] [Tong 23] [Wang 20] [Wei 10] [Yoon 19] [Yu 23] [Zaman 23]
D2: Output modality asymmetry	[Bai 20] [Bardram 12] [Billinghurst 99] [Cavallo 19] [Drey 22] [Gasques 21] [Grandi 19] [Gugenheimer 17] [Gugenheimer 17] [Ihara 23] [Irawati 08] [Jansen 20] [Jing 22] [Johnson 15] [Johnson 21] [Johnson 23] [Jones 2021] [Kim 14] [Kim 19] [Lee 18] [Medeiros 22] [Morishima 12] [Norman 19] [Numan 22] [O’Neill 11] [Piumsomboon 18] [Piumsomboon 19] [Prouzeau 18] [Reilly 10] [Saffo 23] [Teo 19] [Thovari 20] [Tong 23] [Wang 20] [Wei 10] [Yoon 19] [Yu 23] [Zaman 23] [Zhou 19]
D3: Dimensionality asymmetry	[Billinghurst 99] [Grandi 19] [Jansen 20] [Kim 14] [Lee 18] [Medeiros 22] [Saffo 23] [Sakashita 24] [Teo 19] [Tong 23] [Wang 20] [Zaman 23]
D4: User’s mobility asymmetry	[Bardram 12] [Drey 22] [Jing 22] [Johnson 15] [Johnson 21] [Jones 2021] [Kim 14] [Medeiros 22] [Morishima 12] [Norman 19] [Piumsomboon 19] [Prouzeau 18] [Reilly 10] [Saffo 23] [Sakashita 24] [Tong 23] [Zaman 23]
D5: Display space asymmetry	[Bai 20] [Bardram 12] [Drey 22] [Gasques 21] [Grandi 19] [Gronbaek 19] [Irawati 08] [Jansen 20] [Jing 22] [Johnson 15] [Johnson 21] [Johnson 23] [Jones 2021] [Kim 14] [Kim 19] [Lee 18] [Medeiros 22] [Morishima 12] [Numan 22] [O’Neill 11] [Piumsomboon 18] [Reilly 10] [Saffo 23] [Teo 19] [Thovari 20] [Tong 23] [Wei 10] [Yoon 19] [Yu 23] [Zaman 23]
D6: Content access asymmetry	[Bai 20] [Dey 17] [Drey 22] [Gasques 21] [Gronbaek 19] [Gugenheimer 17] [Ihara 23] [Irawati 08] [Jansen 20] [Jing 22] [Johnson 15] [Johnson 21] [Johnson 23] [Kim 14] [Kim 19] [Lee 18] [Morishima 12] [Norman 19] [O’Neill 11] [Piumsomboon 18] [Sakashita 24] [Teo 19] [Thovari 20] [Wang 20] [Wei 10] [Yoon 19] [Yu 23] [Zaman 23] [Zhou 19]
D7: Content layout asymmetry	[Bardram 12] [Billinghurst 99] [Fink 22] [Gronbaek 23] [Gugenheimer 17] [Kim 14] [Norman 19] [Piumsomboon 19] [Reilly 10] [Saffo 23] [Tong 23] [Wang 20] [Zhou 19]
D8: Shared feedback asymmetry	[Bai 20] [Billinghurst 99] [Cavallo 19] [Dey 17] [Drey 22] [Gasques 21] [Grandi 19] [Gugenheimer 17] [Ihara 23] [Irawati 08] [Jing 22] [Johnson 15] [Johnson 21] [Johnson 23] [Jones 2021] [Kim 14] [Kim 19] [Lee 18] [Medeiros 22] [Morishima 12] [Numan 22] [Norman 19] [O’Neill 11] [Piumsomboon 18] [Piumsomboon 19] [Prouzeau 18] [Saffo 23] [Sakashita 24] [Teo 19] [Thovari 20] [Wang 20] [Wei 10] [Yoon 19] [Yu 23] [Zaman 23]