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What And How Together: A Taxonomy On 30 Years Of Collaborative Human-Centered XR Tasks

Ryan K. Ghamandi*
ISUE Lab
University of Central Florida

Yahya Hmaiti†
ISUE Lab
University of Central Florida

Tam T. Nguyen‡
ISUE Lab
University of Central Florida

Amirpouya Ghasemaghaei§
ISUE Lab
University of Central Florida

Ravi Kiran Kattoju¶
ISUE Lab
University of Central Florida

Eugene M. Taranta II‖
ISUE Lab
University of Central Florida

Joseph J. LaViola Jr.**
ISUE Lab
University of Central Florida

Abstract

We present a taxonomy of human-centered collaborative XR tasks. XR technologies have extended into the realm of collaboration, improving the quality and accessibility of teamwork. However, after a comprehensive assessment of the literature on the interaction between XR technologies and collaboration, no comprehensive method that emphasizes task actions and properties exists to classify collaborative tasks. Thus, our suggested taxonomy represents a classification system for collaborative tasks. After conducting a thorough literature review across different research venues, we conducted several exhaustive classification and review cycles for over 800 papers collected, which resulted in 148 papers retained to create the taxonomy. We dissected the actions and properties that the collaborative endeavors and tasks of these papers encompass as well as the types of categorizations and relations these papers illustrate. We expand on the design choices and usage of our taxonomy, followed by its limitations and future work. We built this taxonomy in order to reduce ambiguities and confusion regarding the design and comprehension of human-based collaborative tasks that use XR technology, which could prove useful in aiding the development and understanding of these tasks. Our taxonomy reveals a framework for understanding how collaborative tasks are designed and a systematic way of classifying different methods by which people can collaborate and interact in environments that involve XR, while still promoting efficient communication, teamwork, goal achievement and productivity.

Index Terms: Human-centered computing—Human computer interaction (HCI)—Interaction paradigms—Virtual reality; Human-centered computing—Collaborative and social computing design and evaluation methods; Human-centered computing—HCI design and evaluation methods;

1 Introduction

Collaboration is the process in which people work together to realize a common goal [25, 86, 97, 146, 160]. Such a practice has been common since the dawn of mankind, and with the combination of advanced technological devices, the field of extended reality (XR) collaboration has emerged [88, 100, 163]. Collaboration using XR technologies involves individuals engaging in cooperative endeavors in virtual environments (VE), such that with XR, a large array of different modern co-creation and collaboration tasks (definite pieces of work that are meant to be completed by multiple individuals) was created over the past three decades across several domains [13, 30, 32, 48, 50, 127, 172]. It was found that through the incorporation of XR in collaboration processes several key advantages were uncovered: better communication, remote and real-time collaboration facilitation, immersive simulations, more accessibility and inclusion along with better contextualization and information exchange, etc. [88, 126] As the research work in collaboration is ongoing, the characteristics and properties of collaborative tasks evolve, which brings about a harder categorization process, and even designing efficient collaborative tasks using XR becomes challenging considering that new collaboration elements and properties are introduced [77, 113, 114, 191].

In this paper, we aim to analyze existing collaboration tasks that use XR technologies and classify their elements under the umbrella of a collaborative task taxonomy. To achieve this, we analyzed 148 papers picked from an initial pool of over 800 papers in the extended reality collaborative space to synthesize various collaborative tasks and their properties. The resulting comprehensive taxonomy details actions and properties associated with collaborative tasks. The classification system we propose for tasks performed collaboratively in extended reality expands on the XR collaboration literature by providing a taxonomy that encompasses other related taxonomies and reviews into a central classification for tasks that covers XR-related paradigms.

This paper contributes to XR collaboration by providing a classification of mixed reality tasks. The presented taxonomy through this work affords a classification regardless of the system employed, as well as identifying key actions and properties that XR collaborative tasks possess. We created this taxonomy to create a clearer depiction of these types of tasks to help people have a greater understanding of how they are structured and what they entail.

2 Related Work

Extended Reality technologies afford the facilitation of different forms of collaboration through the different realities in the mixed reality continuum [13, 84]. In such collaborative settings, several elements make up the collaborative task, which can be separated into properties and actions of a task. Prior work that details collaborative task design considerations suggests that the actions taken during a task can consist of environmental observation, locomotion, object selection/manipulation, etc. whereas the properties of a task include task location (virtual and physical) if the task is synchronous or asynchronous, roles of each entity partaking in the task, and the relation between the sub-tasks that constitute a task, etc. [71, 84, 93, 119, 136, 172, 189].

Prior work has shown that collaborative tasks using XR technologies are employed across several industries due to the benefit of having collaborative simulations and experiences similar to real-world scenarios [18, 70, 71, 172]. As the development and research in XR-based collaboration is progressing numerous classifications

*e-mail: ryanghamandi1@gmail.com
†e-mail: Yohan.Hmaiti@ucf.edu
‡e-mail: tamn0928@gmail.com
§e-mail: amirpouya.ghasemaghaei@ucf.edu
¶e-mail: kattoju.ravikiran@gmail.com
‖e-mail: etaranta@gmail.com
**e-mail: jlaviola@ucf.edu

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of related collaborative tasks have been proposed. One such classification system which acts as the basis of many other classifications is the Mixed Reality Spectrum developed by Milgram et al. [100]. Other early classifications which encompass the types of environmental interactions which are fundamental to collaborative scenarios include Bowman's taxonomy of selection/manipulation techniques, which specifies the components of selection, manipulation, and release of objects in VEs [17] and Poupyrev's taxonomy of manipulation techniques which are based on exocentric and egocentric metaphors [125].

Prior work also shows that task analysis systems and methods are in place to aid the design of systems that pertain to tasks in general, not just for collaborative tasks. For example, Annett et al. [4] describe task analysis in a broad sense which applies to all types of tasks, not just ones that exist solely on the mixed reality spectrum. This specific method of task analysis is meant to decompose a task in order to identify the source of its cognitive or physical shortcomings so solutions can be devised for applications such as training scenarios, control tasks, etc. Along the same vein is the guide for engineering and design proposed by Stanton et al. [151], which focuses on using task analysis methodologies for design and evaluation of products and systems. Another example is the guidelines for design and evaluation of VEs proposed by Gabbard et al. [40], which lays out guidelines for environment and interaction design fueled by task analysis. More recent methods of VE design and evaluation have been introduced by Raimbaud et al. [128, 129], which also uses task analysis to drive the evaluation of virtual reality interaction design for construction and Building Information (BIM) related scenarios.

One of the most recent literature reviews on collaborative mixed reality was conducted by Schafer et al. [138] which discusses synchronous remote XR collaborative systems as well as a taxonomy of such systems, but not on the classification of tasks performed using these systems. The survey done by Wang et al. [172] was also conducted with a focus on AR and MR tasks, but these tasks were only physically-based tasks despite them being extracted from different fields (e.g. industrial, medical, etc). Other surveys and classifications conducted discuss other aspects of collaboration such as how collaboration is carried out synchronously or asynchronously in VR and AR [120], user experience in collaborative extended reality [105], how systems are structured for specific types of reality [95], the aspects of collaborative VEs [192], the general state of collaborative work in augmented reality [144], and remote assistance and training in mixed reality environments in relation to what components such scenarios are composed of [34]. These classifications and reviews focus essentially on the systems or aspects of the collaboration instead of classifying the related tasks that people work on using XR collaboration means.

The existing taxonomies and classifications of collaboration using technologies on the XR spectrum provided insight into XR collaboration with a focus on the individual tasks, and the different technical features and aspects that relate to them. While this is beneficial, those taxonomies and classifications do not elaborate comprehensively on tasks across multiple realities. Through our taxonomy, we narrow down the scope to human-to-human collaboration in order to offer a comprehensive classification of the task actions and properties that promote better collaboration between individuals.

3 METHODOLOGY

Through iterating over prior work, we noticed the presence of an extensive collection of research work related to XR technology usage for collaborative tasks. Accordingly, we crafted a taxonomy of collaborative tasks that rely on XR-related interactive technologies, which serves also as a classification that affords to categorize current literature to comprehend different types of collaborative tasks using interactive technologies and understand advancements, potential improvement areas, and determine future work within the field. In this section, we list the procedure and steps taken to curate an archive of applicable publications used to create the taxonomy.

Before moving forward with gathering papers, we first created a taxonomy amongst ourselves to create categories in which to classify information obtained while reading each relevant paper. This part of our methodology was loosely based on the process used by Fagerholm et al. [28] in order to create a basis for our classifications since no relevant task-based taxonomy existed in the first place, as well as to create a starting point for the actual taxonomy. This initial taxonomy was further modified after the information extraction step in order to arrive at the final taxonomy state. We note that the methodology used shares similar elements to the one developed by Moher et al. [102].

To curate an archive of research work and publications to interpret and analyze, we first conducted a systematic search in different relevant digital libraries and repositories, which include *IEEE Xplore*, *ACM Digital Library*, and *Springer*. In order to fine-tune our search to obtain the most relevant results, we chose search keywords that included *"collaboration", "collaboration Tasks", "Asynchronous Collaboration", "Synchronous Collaboration", "Collaboration Framework", "Collaborative Interaction", "Collaborative Virtual Reality Environment", "CVRE", "Virtual Reality", "Augmented Reality", "Mixed Reality", and "Extended Reality"*.

We performed several search queries, yet for ease of result replicability, we share the base query format we followed through a sample query, where the Boolean "AND" joins main terms, and "OR" enables the inclusion of either specified terms or synonyms surrounding it: ***"Collaboration" AND "Collaboration Task" AND ("Virtual Reality" OR "Augmented Reality" OR "Mixed Reality" OR "Extended Reality")***. Moreover, we not only varied the keywords and their order when querying, but we also used search queries where the keywords had their initials lowercase, search queries where all the keywords were uppercase, and also other queries where we used keyword acronyms instead of full words. The searches in these databases generated 800 to 6000 papers each.

After obtaining all these papers, we worked together to filter the papers that would be irrelevant to the taxonomy. We initially defined explicit criteria to determine the relevance of a paper to decide whether it would be excluded or not, and we refined the inclusion and exclusion (EX) criteria as the iteration process went through. We excluded a paper if: **(EX-1)** *The paper was not written in English.* **(EX-2)** *The paper's full-text could not be accessed.* **(EX-3)** *The paper was a poster or a short paper or was not peer-reviewed.* **(EX-4)** *The paper had no contribution relevant to the XR collaboration field.* **(EX-5)** *The paper was not focused on human-centered collaboration (i.e. robot centered collaboration, etc.).*

In the second iteration, we read every paper's title and abstract and then excluded the paper if it was deemed as irrelevant to our investigation, and we also used some exclusion criteria from the ones listed above in the second iteration, and in case we had doubts, we proceeded with exploring the remaining parts of the paper to make a more justified and decisive choice regarding keeping or excluding the paper. If the paper was to be excluded, yet had some slight correlation with our topic or had an important impact in relation to interactive technologies and their usage or just collaboration in settings other than XR, we took extra notes about it to be reviewed later if needed, yet it was still excluded. After this second filtering round, our final corpus of relevant research papers from all the research venues investigated consisted of 847 papers.

After obtaining a comprehensive set of relevant research papers, we extracted and classified information based on the categories of the pre-existing taxonomy. The classification components that were gathered from each paper included basic paper components such as ***Paper Title, Paper Link, Include Paper (Y/N)***, and the other collaboration-related classification components include ***actions taken, information communicated, input and output communication, entities and their roles/statuses, locomotion method,***

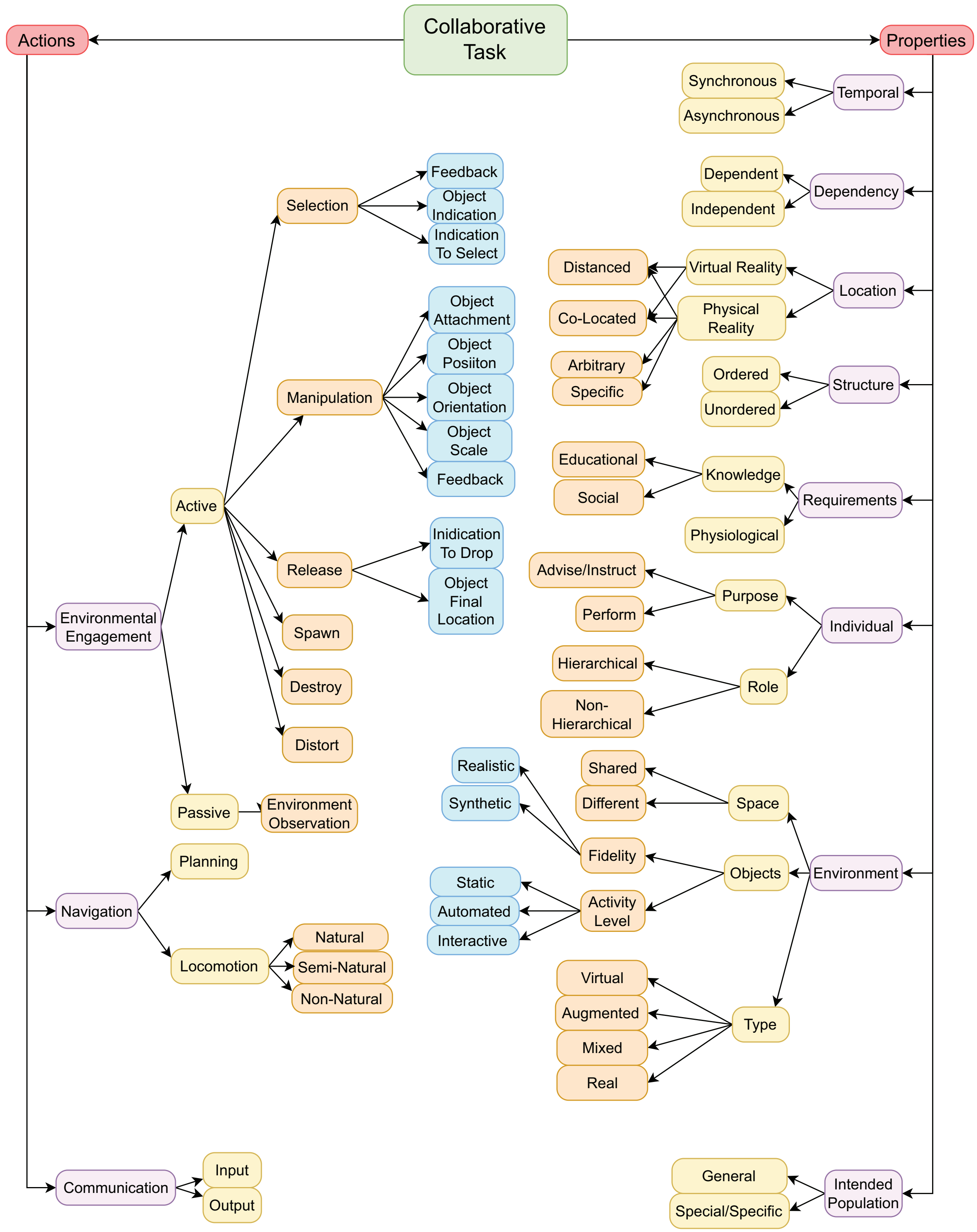

Figure 1: A taxonomy of human-to-human XR collaborative tasks.

temporal state, physical and virtual location(s), physically or virtually co-located, tasks, theory/model/framework, extra notes (if any), measures collected, and potential research gap/limitations.

The reading of the 847 papers was done individually by each author and also through group discussions, and we took detailed notes on each paper based on the pre-existing classifications. Emerging patterns, key components of each paper, and key findings were assessed continuously, and discussed by all the authors. Additionally, if anyone of the authors had some remarks regarding the technology, collaboration task, or content of the paper, an extra notes section was available for each paper considering that those remarks could influence the structure of the taxonomy. While reading each paper, papers that still did not have relevance to the taxonomy were discarded. The final pool of papers consisted of 148 papers.

The purpose of this taxonomy was to present a survey and comprehensive assessment of the collaboration tasks that involve XR interactive technologies present in the literature. Our methodology to build the taxonomy was set based on different methodologies for taxonomies and surveys present in prior work. Additionally, during the multiple filtering phases, we diligently and carefully selected papers to avoid redundant and low-impact references. Furthermore, we collaboratively modified the taxonomy as the filtering and surveying were ongoing, and relied on using Inter-Rater Reliability (IRR) [36] to modify the structure of the taxonomy; as additional categories were proposed to be added to the taxonomy, the authors used IRR to add or discard them. We emphasized getting related work published during the past two decades as older papers would not provide much relevant insight to build a state-of-the-art taxonomy of collaborative tasks in the context of our investigation.

We hope that other researchers that plan to expand on the taxonomy or use it will contribute to expanding the dataset and its content, along with suggesting changes to the classification if present, and overall maintain a dynamic discussion about collaborative tasks and how our presented taxonomy can be updated especially when more collaboration tasks are created and published. Our research questions are ”What specific actions can we classify XR collaborative tasks under?” and ”What specific properties can we classify XR collaborative tasks under?”

4 Taxonomy on Human-Centered XR Collaborative Scenarios

The taxonomy of human-centered collaboration in XR is divided into two main components: ***Actions*** taken related to the task, and the ***Properties*** of the collaborative task, in which we explain each node in depth in the following subsections.

4.1 Actions

During any arbitrary task, individuals that participate in it and choose to progress through it and reach some sort of outcome or goal, achieve this by performing actions related to the task. To this end, such actions can be classified under three main categories: ***Environmental Engagement***, ***Locomotion***, and ***Communication***.

4.1.1 Environmental Engagement

Environmental Engagement refers to the methods by which the user can interact and modify the VE, which we classify into two types: ***Active (e.g. object manipulation)*** and ***Passive (e.g. observing the environment only)***

Active environmental engagement is the interaction with objects in the environment and its components. These manipulations can be achieved through selection, manipulation, release, spawning, destroying, and/or distortion.

Passive environmental engagement occurs when the individual assumes a more passive role and is mostly an observer of the VE, or when they are immersed in the VE and experiencing its content without direct input or active impact on the VE aspects and components.

4.1.2 Navigation

Navigation is the process by which individuals navigate around an environment. Navigation can be split into two components: ***Planning*** (where an individual determines a location where they want to move) and ***Locomotion*** (where an individual moves to a desired location). Locomotion can be further classified into three types: ***Natural*** (e.g. walking), ***semi-natural*** (e.g. scaled walking), and ***non-natural*** (e.g. use of joysticks).

4.1.3 Communication

Communication refers to the sharing of information between individuals. This can be classified as either ***Input*** or ***Output***. ***Input*** refers to the method used to send information to other individuals (e.g. voice, hand gestures, etc.). ***Output*** communication refers to the method used to receive and present information, which can either be visual, auditory, haptic, etc.

4.2 Properties

Every task has some sort of collection of aspects that define the nature of the task, from how individuals perform the task to where the task is performed, among other details. As such, these aspects or properties can be classified under multiple categories: ***Temporal***, ***Dependency***, ***Location***, ***Requirements***, ***Individual***, ***Environment***, ***Structure***, and ***Intended Population***.

4.2.1 Temporal State

Temporal state refers to when individuals are actively working on a task, which can be classified as either ***Synchronous*** or ***Asynchronous***. ***Synchronous temporal*** state means that individuals are actively working on a task together at the same time (simultaneously) while ***Asynchronous temporal*** state means that individuals are actively working on a task at different times [120].

4.2.2 Dependency

Dependency refers to the reliance that a task has on other tasks, which can be classified as either ***Dependent*** or ***Independent***. ***Dependent tasks*** are ones which are dependent on the outcomes of other task(s), while ***independent tasks*** are ones which are not dependent on the outcomes of other task(s).

4.2.3 Location

Location refers to the placement setting of individuals when performing a task. Location can be partitioned into two main categories; the ***physical location*** and the ***virtual location*** of the task.

The physical location refers to where individuals are located in the real world. This can be further broken down into individuals being distanced or co-located, and also into individuals having to be in either a specific or arbitrary location.

The virtual location refers to where individuals are located in a VE (if they happen to be in one). This can be further broken down into individuals being either ***distanced*** or ***co-located*** virtually.

4.2.4 Requirements

Requirements are the specific qualifications or abilities that individuals must possess to perform the task. This can be broken down into two types of requirements: ***Knowledge*** and ***Physiological*** requirements.

Knowledge requirements refer to the intellect or experience that an individual needs to complete a task. This can be further broken down into two types: educational (e.g. knowing a specific subject or topic in-depth) and social (being acquainted with a specific culture).

Physiological requirements refer to the physical capabilities that an individual needs to complete a task (e.g. being able to walk, use both hands, etc.)

4.2.5 Individual

The ***individual*** participating in a task possesses properties of their own in relation to the task. These properties are classified as the individual's ***Purpose*** and ***Role***.

Purpose refers to what an individual is meant to do in regards to a task. This is broken down into the individual either ***performing*** a task or ***advising/instructing*** another individual to complete the task.

Role refers to the part that an individual plays in a task. Roles can either be ***hierarchical*** (where individual(s) has/have authority over others e.g. a mentor and mentee) or ***non-hierarchical*** (where individuals have equal roles, e..g. peers working on a project).

4.2.6 Environment

Environment refers to the place where a task takes place. Every environment can be broken down into three elements: ***Space***, ***Objects***, and ***Type***.

Space refers to the area in which individuals are located. This area can be classified as either ***Shared*** (individuals are in the same area) or ***Different*** (individuals are not in the same area).

Objects include all the entities in the environment. Objects possess the elements of ***Fidelity*** and ***Activity Level***. ***Fidelity*** refers to the quality or exactness of an object compared to the real world. An object's fidelity can either be realistic or synthetic. ***Activity Level*** refers to the degree to which an object can be manipulated in an environment. An object may either be ***static*** (stays constant throughout a task and does not change), ***automated*** (meant to move or change at some point during a task), or ***interactive*** (individuals can interact with the object).

Type refers to where the environment exists on the mixed reality spectrum. An environment's type can either be ***virtual***, ***augmented***, ***mixed***, or ***real***.

4.2.7 Structure

Structure is the order in which sub-tasks of a task must be completed. Tasks can either be ***Ordered*** (sub-tasks must be completed in a specific order to reach an intended goal) or ***Unordered*** (sub-tasks may be completed in any order to accomplish an intended goal).

4.2.8 Intended Population

Intended Population refers to the specific group of individuals that a task is meant to be performed by. Tasks can either have a ***General*** intended population (e.g. anyone is able to participate in the task) or a ***Special/Specific*** population (e.g. firefighters engaging in a training task to prepare for actual fires).

5 Results

In this section, we elaborate using our findings on each node in the taxonomy. We show the classification of tasks from our corpus under the nodes of the actual taxonomy (see Table 1). We note that while we specify percentages for most nodes, they do not always add up to one hundred percent, e.g. ordered and unordered task percentages add up to 100% but synchronous and asynchronous do not; this is because tasks can possess multiple qualities of a property/action.

5.1 Actions

5.1.1 Environmental Engagement

Active environmental engagement involves many specific actions that can be carried out, which are detailed as ***manipulation*** (86.5% of tasks) [24, 26], ***spawning*** (21.6% of tasks) [67, 140], ***destroying*** (20.3% of tasks) [48, 60], ***distortion*** (11.5% of tasks) [29, 181], ***selection*** (86.5% of tasks) [101, 122], and ***release*** (86.5% of tasks) [104, 137]. However, not all objects necessarily go through the process of selection, manipulation, and release. Some objects can undergo only manipulation if they are indirectly manipulated by other objects, e.g. a ball thrown by an individual hits and moves another object when they collide.

Passive environmental engagement, on the other hand, involves a more passive role and is mostly observance of the VE, or immersion in the VE and experiencing its content ***without direct input or active impact*** on the VE aspects and components (100% of tasks). Such an action happens in every task as individuals retrieve information from the environment to make decisions on what to do next, e.g. being a mentee in a collaborative MR-based surgical procedure would closely observe the state of the patient to perform the surgery successfully [43, 155, 156, 161].

5.1.2 Navigation

Navigation allows users to interact, explore, move, and be spatially present in the VE, such that in several collaborative tasks it facilitates moving through multiple environments, searching for critical objects or information, and coordinating with others in the VE to complete tasks, etc. [87]

Our paper corpus is classified under the three classifications accordingly: ***Natural*** *(e.g. walking, 57.4% of tasks) [38, 131],* ***Semi-Natural*** *(e.g. scaled walking, 4.1% of tasks) [38, 111, 150], and* ***Non-Natural*** *(e.g. joysticks, 6.8% of tasks) [37, 42]*

We note that some prior work did not describe the locomotion method used for their task, or simply did not have any, such that the task individuals remained stationary or had very minimal locomotion. Accordingly, we found walking to be the most predominant form of locomotion, as many tasks involved augmented or mixed reality and were more so focused on the development of other actions to complete tasks (such as manipulations) rather than locomotion.

It should be noted that during our initial review of our paper corpus, we had considered placing ***Navigation*** as a sub-node under ***Passive*** Environmental Engagement. As traversing through an environment of any reality medium could fall within ***Environment Observation***, there are some nuances that warrant its respective node and sub-nodes. For example, planning the route of traversal is Passive Environmental Engagement while Locomotion may lead to Active Environmental Engagement should the participants interact with objects during their task(s),

5.1.3 Communication

Communication allows the sharing of information and feedback between the individuals participating in the collaborative task (94.6% of tasks) [54, 56, 70, 164, 190]. Additionally, communication promotes better teamwork, productivity, collaborative learning and problem-solving, and coordination, which drives reaching set common end goals through collaboration. We classify communication as an action composed of two main elements: ***Input*** and ***Output Information***. ***Input Information*** refers to the various methods the communication initiator or sender uses to send information to others, which include *voice, hand gestures, visual feedback, text, media, etc.*. On the other hand, ***Output Information*** refers to how the information sent is then received and presented to the receiver, which can be *visual, auditory, haptic, etc.*.

5.2 Properties

5.2.1 Temporal State

Synchronous tasks tend to rely on real-time interaction and problem-solving, active engagement, live feedback, communication, and coordination between individuals [78, 165, 188] (98% of tasks). Conversely, ***Asynchronous*** tasks allow the individuals partaking in it to work without synchronous and simultaneous engagement and presence, which potentially allows for more flexibility for completing tasks since individuals are able to actively work in their own time. [21, 60, 159] (5.4% of tasks). Many tasks can be performed both synchronously and asynchronously (e.g. working on a shared text document), which extends tasks efficiency, especially if a task that users cannot perform simultaneously at a particular moment can be completed in parallel at different times.

5.2.2 Dependency

If a participant's task success and completion depends on the output and or completion of another task or multiple others, we classify it as ***Dependent*** (54.7% of tasks) [73, 81, 92]. Such tasks tend to rely on synchronization, communication, and clear planning and coordination amongst individuals with the aim of reaching the expected goals without delays or increased wait times for the tasks that follow. On the other hand, other collaborative tasks can be achieved irrespective of other tasks without heavy reliance on the outcome or completion of other tasks, such tasks are classified as ***Independent*** (45.3% of tasks) [76, 80, 118], and they tend to afford more room for individual autonomy and contribution.

After reviewing our paper corpus, we discovered that many various papers whose tasks which were ***Dependent*** in nature also possessed the ***Synchronous*** property. As participants were interacting in real-time with each other, the overall task completion required various exchanges of outputs from other tasks.

5.2.3 Location

In terms of ***Physical Reality***, every individual exists in a discrete space in the real, physical world in which they perform any task; in that case, the task can either be conducted in an ***arbitrary physical location*** (e.g. at one's home) (95.9% of tasks) [26, 183, 186] or may require being in a ***specific location*** (e.g. a lab room or training facility) (4.1% of tasks) [12, 182]. Moreover, when individuals are collaborating, regardless of who is in a VR setting or not, the individual(s) can be either in the same physical area (60.1% of tasks) [2, 14] or at different physical locations (45.3% of tasks) [42, 74].

In contrast, for ***Virtual Reality***, if there are multiple individuals located and immersed in a VE where the collaborative task is occurring, if the entities partaking in the collaboration are located in the same VE, this qualified as ***co-located*** (49.3% of tasks) [46, 141]. However, in the case where those entities are placed in different VEs, or in the same VE but at different locations in it, in that case, the location is qualified as ***distanced*** [21, 85] (15.1% of tasks).

5.2.4 Requirements

In many cases, individuals may have to possess specific skills or abilities in order to complete certain tasks, else they may have difficulty or even the inability to complete the task. Thus, this is why we sought to classify such requirements based of if they are ***Physiological*** (47.3% of tasks) [177, 188] or ***Knowledge-Based*** (13.5% of tasks) [19, 115]. Physiological requirements can be associated heavily with natural and semi-natural locomotion techniques since individuals would have to perform some form of bodily movement to locomote; this means that they must have the physiological capability to do this.

5.2.5 Individual

Hierarchical Roles represent roles where specific knowledge or leadership initiatives are required such that having these roles promotes better collaborative guidance between individuals, better structure, and chain of command, which can ensure the provision of enough task guidance to others, clear accountability, and appropriate allocation of responsibilities (52% of tasks) [115, 121, 152]. On the other hand, ***Non-Hierarchical Roles*** consist of roles attributed to individuals such that they are not distinguishable by the amount of responsibility, authority, or power one has compared to others (62.2% of tasks) [63, 108, 177].

5.2.6 Environment

Objects in the environment have a certain level of detail, which especially depends on whether it is real or virtual and what kind of purpose it serves. By this logic, we classify objects as having a ***Fidelity*** that is either more ***realistic*** (43.9% of tasks) [123, 169] or more ***synthetic/virtual*** [47, 111] (100% of tasks), and also having an ***Activity Level*** related to the amount of interaction a specific object would undergo, with it either being ***static*** (100% of tasks) [135, 145], ***automated***, or ***interactive*** (84.5% of tasks) [162, 187] to some degree.

The environment where the task takes place exists on some part of the mixed reality spectrum, and the tasks involving multiple places may necessitate environments that belong to multiple parts of the mixed reality spectrum [58, 103]. For example, the task might require an environment place that is AR based only, and require another environment that is VR based. Thus, we classify the environment ***Type*** as being either ***Virtual*** (57.4% of tasks) [58, 76], ***Augmented*** (27% of tasks) [141, 175], ***Mixed*** (17.6% of tasks) [5, 158], or ***Real*** (22.3% of tasks) [11, 158].

It should be noted that for VE types, individuals would only be classified as virtually co-located or distanced if multiple individuals are in a VE. For example, if there is a task with one individual in VR and the other in AR, there would be no question of whether individuals are virtually co-located or distanced.

5.2.7 Structure

In a collaborative endeavor, some tasks can follow a certain structure whereas others can be executed without following a pre-defined or set structure. This dissimilarity in the type of structure of collaborative tasks brings about a classification of ***Ordered*** (62.2% of tasks) [49, 121] and ***Unordered*** (37.8% of tasks) [66, 68] tasks structures.

It is worth mentioning that collaborative tasks that possess the ***Ordered*** property may have their individual sub-tasks be ***Unordered***. This means that the sub-tasks can be completed in any order, but progressing through the order of the broader task requires that all of those are to be completed.

5.2.8 Intended Population

We classify the intended population in collaborative tasks as the group of people that the task is aimed toward, either ***General*** (83.1% of tasks) or ***Specific/Special*** (16.9% of tasks). If the task can be executed by any type of individual(s), then the intended population is general [107, 122]. On the other hand, if the task has specific requirements, for example, a task designed to help enhance learning in elementary school teaching, in that case, the intended population is specific and mainly relates to elementary school students and teachers [35, 48].

6 Discussion

While existing taxonomies within the collaborative space encompass the various environment types (***Virtual***, ***Augmented***, ***Mixed***, and ***Real***) individually, they do not consider categorizing them in a comprehensive manner. In our taxonomy, we made sure that we are able to provide classification for tasks under the whole mixed reality spectrum. Moreover, to ensure that we have made a valid classification system for any given human-to-human collaborative task, we focused on first defining the two larger aspects (*actions and properties*) for which we can create sub-nodes that can branch further in the specification.

One of the purposes served by utilizing the taxonomy is to highlight the clarity regarding the characterization of collaborative tasks. In addition, the proposed taxonomy provides a solid foundation to structure different elements in regard to conducting research within this space. Being able to dissect the different elements of a collaborative task, would help with clarity, foster future reproductions of the research conducted, and transfer novel discoveries. With collaborative tasks entailing high levels of contextual data and through different reality perspectives, it is imperative that there should be guidelines and metrics used to classify both the main task and its sub-components. Thus, the evaluation of collaborative task characteristics would be effectively facilitated through our taxonomy. We note that our proposed taxonomy is not meant to be definitive, but

Action ⇒ Environmental Engagement ⇒ Active ⇒ Manipulation	[1–3, 5, 7–12, 14–16, 20, 22–24, 26, 27, 29, 31, 33, 35, 37–39, 41, 42, 44–49, 51–55, 57–59, 61, 62, 62, 64–68, 70, 74–76, 78–83, 85, 90, 92, 94, 96, 98, 99, 101, 104, 106, 108, 109, 111, 112, 115–118, 121–124, 131–134, 137, 139–143, 147–150, 153–159, 161, 162, 164–171, 173–176, 178, 179, 181–188, 190]
Action ⇒ Environmental Engagement ⇒ Active ⇒ Spawn	[11, 19, 24, 38, 42, 46, 48, 49, 60, 67, 68, 79, 83, 99, 109, 110, 112, 140, 143, 150, 156, 158, 159, 165, 168, 169, 182–185, 188, 190]
Action ⇒ Environmental Engagement ⇒ Active ⇒ Release	[1–3, 5, 7–12, 14–16, 20, 22–24, 26, 27, 29, 31, 33, 35, 37–39, 41, 42, 44–49, 51–55, 57–59, 61, 62, 62, 64–68, 70, 74–76, 78–83, 85, 90, 92, 94, 96, 98, 99, 101, 104, 106, 108, 109, 111, 112, 115–118, 121–124, 131–134, 137, 139–143, 147–150, 153–159, 161, 162, 164–171, 173–176, 178, 179, 181–188, 190]
Action ⇒ Environmental Engagement ⇒ Active ⇒ Destroy	[11, 19, 24, 38, 42, 46, 48, 49, 60, 67, 69, 79, 83, 99, 109, 110, 112, 140, 143, 156, 158, 159, 165, 168, 169, 183–185, 188, 190]
Action ⇒ Environmental Engagement ⇒ Active ⇒ Distort	[14, 20, 29, 39, 46, 48, 52–54, 67, 82, 99, 115, 130, 152, 181, 188]
Action ⇒ Environmental Engagement ⇒ Active ⇒ Select	[1–3, 5, 7–12, 14–16, 20, 22–24, 26, 27, 29, 31, 33, 35, 37–39, 41, 42, 44–49, 51–55, 57–59, 61, 62, 62, 64–68, 70, 74–76, 78–83, 85, 90, 92, 94, 96, 98, 99, 101, 104, 106, 108, 109, 111, 112, 115–118, 121–124, 131–134, 137, 139–143, 147–150, 153–159, 161, 162, 164–171, 173–176, 178, 179, 181–188, 190]
Action ⇒ Environmental Engagement ⇒ Passive ⇒ Environment Observation	[1–3, 5–12, 14–16, 19–24, 26, 27, 29, 31, 33, 35, 37–39, 41, 42, 44–49, 51–62, 62–70, 72–76, 78–83, 85, 89–92, 94, 96, 98, 99, 101, 103, 104, 106–112, 115–118, 121–124, 130–135, 137, 139–143, 145, 147–150, 152–159, 161, 162, 164–171, 173–188, 190]
Action ⇒ Navigation ⇒ Locomotion ⇒ Natural	[2, 3, 5, 7, 9, 11, 12, 14, 15, 19, 21–24, 26, 31, 38, 39, 41, 42, 46, 48, 52, 55, 56, 58, 60, 62, 62, 65, 70, 73–75, 80–83, 85, 89, 90, 92, 94, 101, 103, 104, 107–109, 115–117, 121–124, 130–132, 137, 139, 142, 143, 145, 153, 155–159, 161, 165–167, 169, 170, 174, 177–179, 182, 184–186, 190]
Action ⇒ Navigation ⇒ Locomotion ⇒ Semi-Natural	[38, 61, 70, 111, 150, 177]
Action ⇒ Navigation ⇒ Locomotion ⇒ Non-Natural	[12, 37, 38, 42, 83, 94, 122, 157, 177, 183]
Action ⇒ Communication ⇒ Input and Output	[1–3, 5–9, 11, 12, 14–16, 19–24, 26, 27, 29, 31, 33, 35, 37, 39, 41, 42, 44–49, 51–57, 59, 61, 62, 62–70, 72–76, 78–83, 85, 89–92, 94, 96, 98, 99, 101, 103, 106–112, 115–118, 121, 123, 124, 130–135, 139–143, 145, 147–150, 152–159, 161, 162, 164–171, 173–181, 183–188, 190]
Properties ⇒ Temporal ⇒ Synchronous	[1–3, 5–12, 14–16, 19–24, 26, 27, 29, 31, 33, 35, 37–39, 41, 42, 44–49, 51–59, 61, 62, 62–70, 72–76, 78–83, 85, 89–92, 94, 96, 99, 101, 103, 104, 106–109, 111, 112, 115–118, 121–124, 130–135, 137, 139–143, 145, 147–150, 152–159, 161, 162, 164–171, 173, 174, 176–185, 185–188, 190]
Properties ⇒ Temporal ⇒ Asynchronous	[21, 39, 60, 98, 110, 159, 175, 182]
Properties ⇒ Dependency ⇒ Dependent	[1, 5–8, 12, 14–16, 20, 22, 23, 29, 31, 39, 41, 44–46, 48, 51, 52, 57, 59, 64–66, 70, 72, 73, 79, 81, 82, 89, 90, 92, 96, 99, 101, 104, 106, 107, 110, 112, 115, 117, 121, 123, 131–135, 137, 141–143, 147–150, 152–154, 158, 159, 161, 164, 165, 167, 169, 170, 173, 175, 176, 179, 181, 182, 184, 185, 188]
Properties ⇒ Dependency ⇒ Independent	[2, 3, 9–11, 19, 21, 24, 26, 27, 33, 35, 37, 38, 42, 47, 49, 53–56, 58, 60–62, 62, 63, 67–69, 74–76, 78, 80, 83, 85, 91, 94, 98, 103, 108, 109, 111, 116, 118, 122, 124, 130, 139, 140, 145, 155–157, 162, 166, 168, 171, 174, 177, 178, 180, 183, 186, 187, 190]
Properties ⇒ Location ⇒ Virtual Reality ⇒ Distanced	[21, 31, 33, 39, 42, 81, 82, 85, 89, 90, 98, 103, 110, 124, 139, 145, 150, 159, 175, 176]
Properties ⇒ Location ⇒ Virtual Reality ⇒ Co-Located	[2, 6–8, 10, 12, 15, 19, 22–24, 26, 27, 29, 37–39, 41, 45–47, 52–54, 56, 57, 62, 62–64, 66, 67, 69, 70, 72, 75, 76, 83, 92, 94, 96, 99, 101, 103, 104, 106, 107, 109, 111, 112, 115–117, 121, 122, 131–134, 137, 141, 147, 157, 161, 166, 167, 171, 177, 179, 183, 186, 187, 190]
Properties ⇒ Location ⇒ Physical Reality ⇒ Distanced	[1, 5, 9, 12, 16, 22, 23, 26, 33, 35, 39, 42, 44, 48, 49, 51, 57, 59, 62, 62, 65, 66, 68, 69, 72–76, 79–81, 85, 90, 92, 94, 98, 99, 103, 106, 110–112, 123, 124, 133–135, 143, 145, 147, 148, 150, 152, 153, 155–158, 162, 165, 169, 173, 182, 185–187]
Properties ⇒ Location ⇒ Physical Reality ⇒ Co-Located	[2, 3, 5–8, 11, 12, 14, 15, 19–22, 24, 27, 29, 31, 37–39, 41, 45–47, 52–56, 58, 60–64, 67, 70, 78, 82, 83, 89, 91, 94, 96, 101, 103, 107–109, 115–118, 121, 122, 130–133, 137, 139–142, 149, 150, 154, 159, 161, 164, 166–168, 170, 171, 174–181, 183, 184, 187, 188, 190]
Properties ⇒ Location ⇒ Physical Reality ⇒ Arbitrary	[1–3, 5–11, 14–16, 19–24, 26, 27, 29, 33, 35, 37–39, 41, 42, 44–49, 51–59, 61, 62, 62–70, 72–76, 78–83, 85, 89–92, 94, 96, 98, 99, 101, 103, 104, 106, 108–112, 115–118, 121–124, 130–135, 137, 139–143, 145, 147–150, 152–159, 161, 162, 164–171, 173–175, 177–181, 183–188, 190]
Properties ⇒ Location ⇒ Physical Reality ⇒ Specific	[12, 31, 60, 107, 176, 182]
Properties ⇒ Requirements ⇒ Knowledge	[1, 12, 19, 22, 23, 35, 39, 48, 60, 63, 67, 82, 99, 106, 107, 115, 171, 175, 176, 188]
Properties ⇒ Requirements ⇒ Physiological	[2, 5, 9, 11, 12, 14, 19, 21, 24, 29, 33, 35, 38, 39, 41, 42, 47, 49, 58, 60, 62, 65, 69, 73, 75, 76, 79–81, 83, 85, 89, 101, 103, 106, 107, 109, 112, 116, 123, 124, 130–132, 140, 141, 143, 145, 150, 155–159, 161, 168, 169, 174, 175, 177–182, 184–186, 188, 190]
Properties ⇒ Individual ⇒ Role ⇒ Hierarchical	[1, 2, 5, 7, 9–12, 15, 19, 23, 26, 37, 41, 42, 44, 48, 49, 53, 54, 58, 59, 61, 62, 62, 65, 68, 73–75, 78–81, 89, 90, 94, 98, 101, 106–112, 115, 121, 123, 124, 134, 135, 139, 141, 143, 145, 148–150, 152–158, 161, 162, 164, 165, 167–169, 173, 178, 185, 188]
Properties ⇒ Individual ⇒ Role ⇒ Non-Hierarchical	[3, 3, 6, 8, 14, 16, 19–22, 24, 27, 29, 31, 33, 35, 38, 39, 41, 45–47, 51, 52, 52–57, 57, 60, 63, 64, 66, 67, 69, 69, 70, 72, 76, 82, 83, 85, 91, 92, 96, 99, 103, 104, 106–108, 111, 112, 115–117, 117, 118, 122, 130–133, 137, 140–142, 147, 153, 157, 159, 166, 167, 170, 170, 171, 174, 176, 177, 179, 180, 180–187, 190]
Properties ⇒ Environment ⇒ Objects ⇒ Fidelity ⇒ Realistic	[1, 5, 9, 11, 16, 19, 42, 44, 46, 48, 49, 55, 56, 58–60, 65, 68, 73–76, 78–82, 96, 98, 103, 107, 108, 110, 117, 118, 121–123, 130, 140–143, 145, 148, 152–156, 158, 159, 161, 165, 169–171, 173–175, 179, 182, 184, 185, 188]
Properties ⇒ Environment ⇒ Objects ⇒ Fidelity ⇒ Synthetic	[1–3, 5–12, 14–16, 19–24, 26, 27, 29, 31, 33, 35, 37–39, 41, 42, 44–49, 51–62, 62–70, 72–76, 78–83, 85, 89–92, 94, 96, 98, 99, 101, 103, 104, 106–112, 115–118, 121–124, 130–135, 137, 139–143, 145, 147–150, 152–159, 161, 162, 164–171, 173–188, 190]
Properties ⇒ Environment ⇒ Objects ⇒ Activity Level ⇒ Static	[1–3, 5–12, 14–16, 19–24, 26, 27, 29, 31, 33, 35, 37–39, 41, 42, 44–49, 51–62, 62–70, 72–76, 78–83, 85, 89–92, 94, 96, 98, 99, 101, 103, 104, 106–112, 115–118, 121–124, 130–135, 137, 139–143, 145, 147–150, 152–159, 161, 162, 164–171, 173–188, 190]
Properties ⇒ Environment ⇒ Objects ⇒ Activity Level ⇒ Interactive	[1–3, 5, 7–12, 14–16, 20, 22, 24, 26, 27, 29, 31, 33, 35, 37–39, 41, 42, 44–49, 51–55, 58, 59, 61, 62, 62, 64–68, 70, 74–76, 78–83, 85, 90, 92, 94, 96, 98, 99, 101, 104, 106, 108, 109, 111, 112, 115, 116, 118, 121–124, 131–134, 137, 139–143, 147–150, 153–159, 161, 162, 164–171, 173–176, 178, 179, 181–188, 190]
Properties ⇒ Environment ⇒ Type ⇒ Virtual	[1, 2, 6–8, 10, 12, 15, 19, 21–24, 26, 27, 29, 35, 37–39, 41, 45, 47, 52–54, 56–58, 62, 62–64, 66, 67, 69, 70, 72, 76, 78, 82, 83, 85, 89–92, 94, 96, 99, 101, 103, 104, 106, 109, 111, 112, 116, 117, 124, 131, 132, 134, 137, 139, 145, 147, 149, 150, 154, 157, 159, 162, 164, 166, 167, 171, 176–179, 183, 186, 187, 190]
Properties ⇒ Environment ⇒ Type ⇒ Augmented	[1, 3, 14–16, 19, 49, 55, 56, 58–61, 65, 68, 73, 75, 80, 103, 107, 110, 118, 123, 140–143, 145, 148, 150, 152, 153, 165, 168, 170, 174, 175, 182, 184, 188]
Properties ⇒ Environment ⇒ Type ⇒ Mixed	[1, 5, 9, 11, 23, 42, 44, 48, 68, 74, 79, 81, 82, 121, 122, 154–156, 158, 159, 161, 169, 173, 174, 185, 185]
Properties ⇒ Environment ⇒ Type ⇒ Real	[1, 3, 5, 9, 11, 14–16, 37, 42, 61, 65, 68, 73, 74, 78, 79, 96, 103, 109, 123, 142, 143, 153, 154, 158, 168, 170, 174, 179, 182, 184, 185]
Properties ⇒ Structure ⇒ Ordered	[1, 5–9, 12, 15, 21–24, 27, 29, 31, 33, 35, 37–39, 41, 42, 47, 49, 51–54, 56, 58–60, 63–65, 70, 72, 73, 75, 76, 79, 83, 85, 90, 92, 94, 96, 101, 103, 104, 106, 108–112, 116–118, 121–124, 131, 132, 137, 140, 142, 143, 145, 147, 149, 150, 153, 155–157, 159, 164, 166, 167, 169, 170, 176–179, 183, 185–187, 190]
Properties ⇒ Structure ⇒ Unordered	[2, 3, 10, 11, 14, 16, 19, 20, 26, 44–46, 48, 55, 57, 61, 62, 62, 66–69, 74, 78, 80–82, 89, 91, 98, 99, 115, 130, 133–135, 139, 141, 148, 152, 154, 158, 161, 162, 165, 168, 171, 173–175, 180–182, 184, 185, 188]
Properties ⇒ Intended Population ⇒ Specific/Special	[1, 2, 5, 6, 12, 16, 19, 22, 23, 31, 35, 39, 48, 53, 54, 67, 99, 115, 118, 130, 166, 176, 180, 181, 188]
Properties ⇒ Intended Population ⇒ General	[3, 7–11, 14, 15, 20, 21, 24, 26, 27, 29, 33, 37, 38, 41, 42, 44–47, 49, 51, 52, 55–62, 62–66, 68–70, 72–76, 78–83, 85, 89–92, 94, 96, 98, 101, 103, 104, 106–112, 116, 117, 121–124, 131–135, 137, 139–143, 145, 147–150, 152–159, 161, 162, 164, 165, 167–171, 173–175, 177–179, 182–187, 190]

Table 1: Full classification of collaborative tasks from our paper corpus under nodes of the taxonomy.

rather a milestone in the categorization efforts of collaborative tasks among all environment types and to fill in a gap in the literature in terms of the classification of collaborative tasks in the XR spectrum. Further elaboration, expansion, and refining by the community are welcomed in order to take full advantage of what we have proposed.

Our taxonomy can still benefit from being developed based on collaborative tasks using interactive XR that can be obtained through marketed apps and other non-scholarly sources. Furthermore, we emphasize that our goal in this work was to provide a meaningful, valuable, and comprehensive assessment and structure to better understand the field of human-centered XR collaborative tasks. Thus, the core insights and relations established through our taxonomy remain insightful and valuable as a representation of what is established in the field even if potential minor variations to the taxonomy can emerge if dissimilar assessment criteria are used.

In order to use the taxonomy provided, the main step that must be followed is to remember that every arbitrary task that is to be classified under the taxonomy will always have actions and properties, so tasks will always possess attributes from subnodes of both actions and properties. After considering this step, classification is a matter of asking the question of if the task qualifies of possessing the attribute of the subnode in question. This is demonstrated in Table 1, which shows the classifications of papers into most nodes on the taxonomy itself.

6.1 Limitations and Future Work

This taxonomy focused solely on human-to-human collaboration, without considering other entities such as machines or animals. Consequently, future research should consider incorporating such entities in future classifications of collaborative tasks. Another type of classification that is worth mentioning for the future is that of the types of systems or software/hardware that tasks require, which might reduce some ambiguity in terms of the types of technologies that an arbitrary task would normally require (e.g. if the task was AR-based, it may use either a head-mounted display or a smartphone, or even be applicable to both). Additionally, to maximize the usage and value of our taxonomy to the research community, we plan to evaluate uncommon features of collaborative task properties, for example, graphics dependency, the degree/possibility of the task being executed by individuals outside the specified population for the task, and the possibility of the task to be executed across different devices/XR technologies, and so on.

It is also worth mentioning that the initial collection of research papers required using a different set of keywords by our authors for optimized results, and we suspect that if new combinations of keywords were used, different results could have been obtained. Thus, keyword selection in order to conduct literature reviews is of essential matter for future investigations to reduce initial biases even if minimal, and future investigations could consider producing standards for keyword selection.

Furthermore, classifications for automated objects and indirect manipulation were not displayed in Table 1 as these attributes existed subtly in many papers and were ambiguously talked about; therefore, it was difficult to pinpoint an exact number of papers that existed for these classifications and thus they were excluded. Classifications for shared and different environments were also excluded from the table as they are inferred by co-location either virtually or physically.

It should also be noted that there is some degree of subjectivity to how every individual would classify a task for some nodes on the taxonomy, and as such there would be instances of disagreeability for some classifications among individuals.

6.2 Under-Researched Areas

Important advancements were made in collaborative XR. However, there are research directions in this field that could use more attention based on our observations while synthesizing task information for the constructed taxonomy from the paper corpus we went through, which could improve the overall quality of XR collaboration.

6.2.1 Asynchronous Tasks

As described before, tasks can either be classified as synchronous or asynchronous, or even both. However, most tasks observed were synchronous, with only 5.4% of all papers being partially or fully asynchronous. Asynchronous tasks can be particularly useful in scenarios where individuals have difficulty in working simultaneously e.g. being in different time zones or having to work on a separate subtask. Asynchronous capabilities would provide solutions to these cases, with work being done in this area helping to identify which practices would best improve XR collaboration overall.

6.2.2 Navigation

Navigation is a primitive action that any individual undertakes in numerous tasks, with over 50% of all tasks encountered in the corpus having some sort of navigation. Even though navigation widely exists in collaborative scenarios, not much research has been conducted to investigate the use of navigation in these tasks, especially locomotion techniques, as only 2 of the papers in our corpus directly investigated navigation techniques. Expansion on the use of various navigation techniques, especially natural ones, in these scenarios would be useful as they would allow people to navigate with more ease, especially with the arbitrary nature that a task may be of.

6.2.3 Communication Output

Communication is the method of transferring information between entities, and humans can receive that information through multiple senses; sight, hearing, touch, taste, and smell. While visual and auditory output channels of information reception are very common for receiving information in XR collaboration and have been researched extensively, other methods (haptic, olfactory, gustatory) are not as common; few papers used haptics to deliver information to individuals, and only one paper investigated the use of a gustatory interface for communication, but as an input method. These lesser-used methods of communication output have the potential to provide information to individuals in a subtle and even natural way in addition to the more commonly used senses, which can increase the collaborative capabilities of individuals.

7 Conclusion

Through this work, we created a taxonomy of collaborative tasks in the realm of XR technologies. Our taxonomy serves as an illustration of the main components of collaborative tasks based on the actions taken when performing the task, and the properties of each task. The taxonomy we present is the outcome of a thorough literature review, classification, and thematic analysis of the research work on XR collaboration. Our dataset of papers analyzed was gathered from principal research venues, while not necessarily complete, it has permitted us to expand beyond what is already known about collaborative tasks by producing a comprehensive collaboration taxonomy across the mixed reality spectrum.

We hope that our research work will contribute to advancing research efforts on the intersection of collaboration and interactive technologies. Our taxonomy can be extended to future investigations, and additional classifications and strategies could be extracted based on our methodology and later be applied to different datasets, or after adding newer papers to our existing dataset, or even to uncover and reach other goals expected from collaboration.

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