Conceptualizing Interactions of Augmented Reality Solutions

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Abstract

The rapid evolution of augmented reality has resulted in an ever-increasing number of applications in a wide range of industries and services. Despite this progress, there is still a lack of conceptual understanding of AR interactions and the entire solution space. To bridge this gap, we conceptualize AR solution interactions and provide a comprehensive taxonomy. To represent the state-of-the-art, we build upon an extensive literature review. The resulting taxonomy consists of seven dimensions that encompass 29 characteristics. We contribute to the understanding of AR interactions and, as a result, the applicability of AR solutions in businesses by developing the taxonomy. Likewise, the taxonomy can guide the design of AR solutions as it convincingly describes the solution space.

1. Introduction

The applicability of augmented reality (AR) for business and consumer solutions increased tremendously in recent years. A wide range of solutions applies in various industries, such as technical services [1], healthcare [2], logistics [3], infrastructure maintenance [4], consumer goods [5, 6, 7], as well as mobile and stationary gaming [8, 9]. Despite the increasing application of AR in business contexts, there is still a lack of systematic guidance for designing and orchestrating interactions with AR systems. Even though AR and taxonomies are both areas of interest in IS research, there is little research to date. Although preliminary work exists in the HCI domain, there is no recent taxonomy for conceptualizing AR interactions. Back in the 1990s, Bowman [10] developed a general framework for conceptualizing interaction techniques in immersive virtual environments, but it does not address AR and thus does not leverage AR's specific potential. Additionally, the hardware options were not as mature as they are now. Benford et al. [11] mention several existing taxonomies for input devices, but these do not focus on AR specifically.

As the capabilities of AR increase and novel modalities emerge, the need to systematize AR interactions to foster understanding of applications and guide the design of solutions rises. A systematization of atomic AR interactions to support the design and development of new AR solutions appears highly beneficial, particularly for service design and modeling AR processes [12]. Atomic interactions are, in this regard, the most granular interactions between users and AR devices. An example on the HoloLens 2 for such an atomic interaction is opening a menu by selecting a button presented on the user's palm. The focus is not on what the interaction explicitly aims for, e.g., object creation or manipulation, but much more on the activity of the interaction itself. For this reason, we address the following research question: *How can atomic interactions with AR systems be systematically classified to support service design and AR application development?*

To bridge this gap and take recent findings into account, we conducted a systematic review of literature on interactions and applications of AR to conceptualize interactions of AR solutions. As a result, we create a concise taxonomy that aids in understanding, assessing, and designing AR solutions in terms of interaction patterns. The guiding meta-characteristic for taxonomy development is *"user interaction within services in the realm of AR".* In this regard, we identified seven core dimensions and 29 characteristics in total.

The remainder of the paper is structured as follows: the next section presents related work and lays the core foundations regarding AR. Then we describe our overall research design, the literature review, and the development of the taxonomy. In the fourth section, we introduce the taxonomy of interactions for AR, followed by an in-depth discussion. Finally, we conclude and discuss our paper's contribution as well as potential future research directions.

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2. Related work

2.1. Taxonomy research

Taxonomies are defined as “systems of groupings that are derived conceptually or empirically” [13:338]. Taxonomies attempt to conceptualize objects in a domain of interest to aid researchers and practitioners in their understanding. Taxonomies consist of dimensions that include mutually exclusive and collectively exhaustive characteristics, which means that every object must have one of the dimension’s characteristics. However, no object can have two different characteristics in one dimension [13]. Nickerson et al. [13] propose a method for systematic taxonomy development widely used in the IS domain. It begins with identifying a meta-characteristic for the taxonomy, which serves as the central question. Following that, ending conditions should be defined, which can be objective or subjective. Subsequently, taxonomy development begins, following either an empirical-to-conceptual or a conceptual-to-empirical approach. Iteratively, the taxonomy develops by discovering new dimensions and characteristics until the predefined ending conditions are met.

2.2. Augmented reality

AR has grown in popularity in recent years, and it is increasingly used in organizations [14] and the gaming industry [9, 15]. However, AR is not a new phenomenon, having its beginnings in the 1960s [16]. According to Milgram [17], AR can be positioned on a continuum between an entirely virtual world – also called virtual reality (VR) – and reality. This continuum is called the virtuality continuum and includes various forms of mixed reality (MR) between the two extremes. In the case of AR, virtual elements augment reality, but the reality is still predominant. If virtual overlays are in focus, but parts of reality are still present, the author speaks of augmented virtuality (AV). In this paper, we only consider AR as a manifestation of MR. Azuma [18] defines AR as the combination of real and virtual elements, whereas an AR solution allows for real-time interactions, and virtual objects are registered in three-dimensional space.

In contrast to traditional desktop interfaces, AR solutions deliver visual information in a more immersive and spatial manner [17], necessitating the development of new ways of interaction, i.e., the exchange of information between systems and users. A recent study shows that AR interaction techniques are a major topic in human-computer interaction research because AR applications’ usefulness depends on the interaction with the AR user interface, including methods to let the user provide input to the systems [19]. While traditional desktop interfaces typically use a keyboard and mouse as input devices to enable the user to provide information to the system, AR solutions give a wider variety of interaction options, e.g., through various input sensors like microphones, tracking cameras and gyroscopes. Based on this multitude of possibilities, it is necessary to understand interactions in AR better [12]. To achieve such understanding, we propose the following research design to develop a taxonomy of AR interactions.

3. Research design

To bridge the identified gap concerning a taxonomy for AR interactions, we conduct the following research: our approach consists of two phases. The first one is a thorough literature review on interactions with AR solutions in the IS and HCI communities. The identified literature serves as the foundation for taxonomy development. Following that, we create the taxonomy in six iterations.

3.1. Literature review

We started by conducting a structured literature review based on Webster and Watson [20] and vom Brocke et al. [21] to identify literature dealing with interactions in AR solutions.

We used the query *(interact* OR interface OR input) AND (“augmented reality” OR “mixed reality” OR “smart glass*”)* for our keyword search. We limited our search to the title, keywords and abstract, where possible. We set no time restrictions and only looked at peer-reviewed articles. Litsonar (litsonar.com) assisted in the generation of search queries for the databases. Included databases were (1) ACM Digital Library (ACM DL), (2) AIS Electronic Library (AISeL), (3) EBSCO Business Source Complete (EBSCO), (4) IEEEXplore, (5) ProQuest, (6) ScienceDirect (SD), (7) ScholarSpace (SchS), and (8) SpringerLink. We began our search within the IS community and then broadened it to include selected HCI outlets. Regarding IS literature, we included the “Senior Scholars’ Basket of IS Journals”, “Business & Information Systems Engineering”, “Communications of the AIS”, “Information & Management”, and “Journal of Information Technology Theory and Application”, as well as the IS Conferences “International Conference on Information Systems”, “European Conference on Information Systems”, “Hawaii International Conference on System Sciences”, “Americas Conference on Information Systems”, “Pacific Asia Conference on Information Systems”, “International

Conference on Wirtschaftsinformatik", and "International Conference on Design Science Research in Information Systems and Technology". We also added the journal "AIS Transactions on Human-Computer Interaction" for more HCI literature within the IS community. Furthermore, we included the HCI outlets "ACM Transactions on Computer-Human Interaction", "IEEE Transactions on Knowledge and Data Engineering", "IEEE Transactions on Mobile Computing", "IEEE Transactions on Pattern Analysis and Machine Intelligence", "IEEE Transactions on Services Computing", "IEEE Transactions on Software Engineering", "IEEE Transactions on Systems, Man, and Cybernetics, Part B (Cybernetics)", "IEEE Transactions on Visualization and Computer Graphics", "IEEE Transactions on Computers", "IEEE Transactions on Information Theory", "IEEE Transactions on Multimedia", "IEEE Transactions on Robotics", and "IEEE Intelligent Systems".

Table 1. Literature review

	Database	1st round	2nd round	Relevant for taxonomy
IS	AISeL	24	21	10
	EBSCO	3	2	2
	IEEEXplore (only HICSS)	6	3	3
	ProQuest	0	-	-
	SD	0	-	-
	SchS	13	11	7
	SpringerLink	21	6	2
HCI	ACM DL	18	12	9
	IEEEXplore	224	46	18
	Total	309	101	51

We reviewed 309 papers in total (see table 1). Two independent researchers carried out the literature review.

The inclusion criteria were as follows: articles should contain a focus on AR or MR solutions and we considered both the implementation of AR using HMDs, as well as mobile or projection-based AR. In addition, papers had to address interactions with the AR or MR solution. We included case studies with concrete implementations as well as more theoretical and conceptual articles dealing with interactions.

We sorted out 208 papers during the first round by scanning the title, keywords, and abstract. As a result, we had 101 papers for the second round of review. In the second round, we examined the papers in more detail and coded them for further taxonomy development regarding essential keywords. In doing so, we highlighted meaningful passages in the text that related to our research question and met the meta-characteristics described in the following section and recorded the keywords in an Excel spreadsheet to use as input for taxonomy development. We completed the review process with 51 papers after the second round of literature review. Twenty-four of the articles are from the IS community, and 27 are from the HCI community. We proceeded with the taxonomy development with these 51 papers.

3.2. Taxonomy development

We created the taxonomy using the methodology described by Nickerson et al. [13]. Figure 1 depicts the development process over six iterations. We defined *"atomic user interaction within services in the realm of AR"* as our meta-characteristic. We are not interested in the context in which the AR solution is deployed or entire AR applications but take a much broader perspective and look at any atomic user interactions and their technical constraints. Nickerson et al. [13] provided objective and subjective ending conditions, which we both used. As objective ending conditions, we applied that we examined a representative sample of the literature and that no dimensions or characteristics were added, merged, or split in the previous iteration. In addition, we made sure that at least one object was classified for each characteristic. We considered another essential point that the dimensions, characteristics, and cells are unique and not duplicated. Subjective ending conditions include attributes such as conciseness, robustness, comprehensiveness, extensibility, and explainability. More concretely, this means that the number of dimensions is within a reasonable range and is neither overwhelming nor too small to be meaningful. In this context, five to nine dimensions are considered an adequate guideline to meet the end condition. Regarding robustness, we examined whether the dimensions and characteristics allow for sufficient differentiation. The comprehensibility criterion states that all objects should be classifiable using the taxonomy. We investigated the latter two factors and explainability by repeatedly applying examples to our taxonomy. Extensibility is given when new dimensions and features are easy to add so that the taxonomy is always up to date. We verified this by considering other focal points and evaluating extensibility with this view.

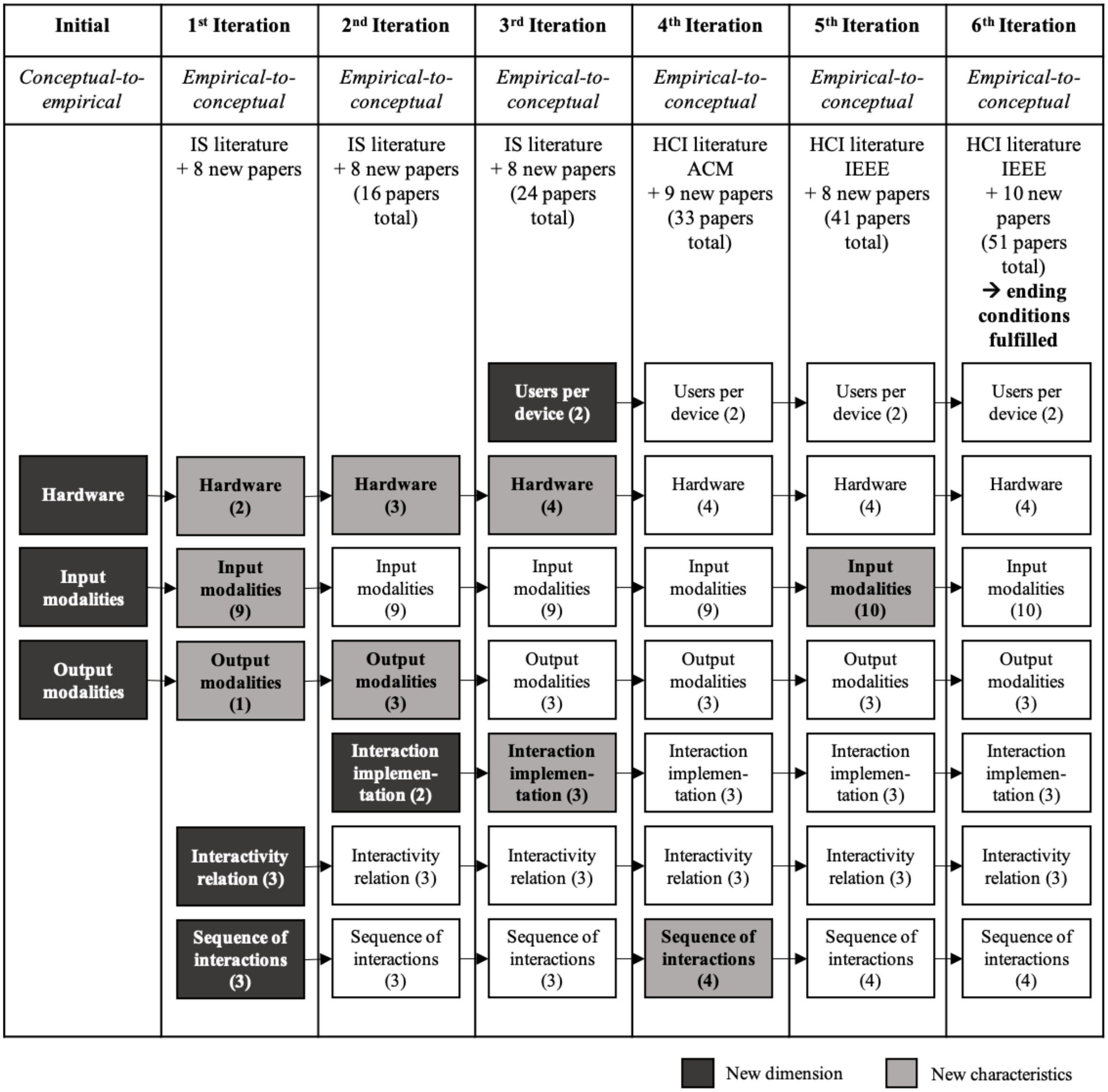

Figure 1. Development of taxonomy dimensions and characteristics (adapted from [22])

We followed a conceptual-to-empirical iteration before the first iteration because Nickerson et al. recommend this approach when “little data are available[,] but the researcher has [a] significant understanding of the domain” [13:345]. Following this approach, we conceptualized the *hardware*, *input modalities*, and *output modalities* dimensions from the researchers’ expertise. In the subsequent iterations, we used the empirical-to-conceptual approach to validate our assumptions.

As data, we used the results of our literature review, and in this way, we identified the objects we aim to classify with our taxonomy. We did this by documenting single characteristics in an Excel sheet and discussed the characteristics with the independent researchers after each iteration. In this way, we could cluster and assess the characteristics onto the dimensions and afterward combine or split characteristics and dimensions if needed. We chose a random sample of eight IS papers for the first iteration, validated our initial dimensions *hardware*, *input modalities*, and *output modalities*, and added two new dimensions: *interactivity relation* and *sequence of interactions*. For the second iteration, we added eight more IS papers and were able to add the dimension *interaction implementation* and several new characteristics to existing dimensions. We included the last eight IS papers in the third iteration, added the dimension *users per device,* and added new characteristics to two existing dimensions. We decided to continue the process with HCI literature because we have not yet met our ending conditions. We added nine papers from the ACM DL database in the fourth iteration. As a result, we discovered a new characteristic. In the fifth iteration, we examined eight HCI papers from IEEEXplore and added one characteristic. In the sixth and final iteration, we analyzed the remaining set of ten IEEEXplore papers and met the objective and subjective ending conditions described above after this iteration. Thus, all of our ending conditions were fulfilled, and the taxonomy development was completed.

4. Taxonomy of interactions for augmented reality

Our taxonomy is composed of 29 characteristics distributed across seven dimensions (see table 2). While the characteristics are collectively exhaustive, we deviate from Nickerson et al. [13] by not requiring mutual exclusiveness to be fulfilled everywhere. This is due to the multimodality of AR solutions, which may include multiple input and output modalities simultaneously. In the following, we describe each of the seven dimensions and the subsumed characteristics in more detail.

D_1 Users per device: AR solutions can be used by a single user or multiple users concurrently. According to our analysis, the vast majority of the articles – 49 out of 51 – describe ***single-user*** settings. We classified the solution as ***multi-user*** if it involves more than one user simultaneously, as shown in the cases of Benford et al. [23] and Enyedy et al. [24]. Both articles describe a multi-user setting in which several users share a virtual and physical space. One device per user is used in the first case, but they share the same virtual and physical space. Multiple users are present in the same space in the latter case, but only one device is used for all of them.

D_2 Hardware: The implemented hardware significantly impacts how the user interacts with the AR solution. Four major characteristics have been identified: ***mobile AR*** [9, 11, 14, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34], such as smartphone or tablets, and ***HMDs***, including monocular [29, 30, 35] and binocular [11, 14, 26, 28, 29, 30, 31, 31, 32, 33, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44, 45, 46, 47, 48, 49, 50, 51, 52], are the most common hardware options. ***Projection-based AR*** [14, 24, 53] and ***desktop AR*** [14, 31, 54] both use a static non-mobile environment, with the former using projectors for augmentation and the latter describing a static desktop setting. The hardware also influences whether hands-free interaction is possible. Accordingly, HMDs, for example, are likely to support hands-free interaction patterns.

Table 2. Taxonomy of augmented reality interactions

Dimensions	Characteristics									
D_1 Users per device	Single-user	Multi-user								
D_2 Hardware	Mobile AR	HMDs	Projection-based AR	Desktop AR						
D_3 Input modalities	Voice	Touch	Gestures	Free body movement	Gaze	Sensor	Eye-tracking	Video/ image	BCI	Generic input device
D_4 Output modalities	Haptic feedback	Visual feedback	Auditory feedback							
D_5 Interaction implementation	Virtual object selection	Physical object selection	Virtual object manipulation							
D_6 Interactivity relation	Digital objects	Physical objects	People							
D_7 Sequence of interactions	Frequency	Duration	Variety	Concurrency						

D_3 Input modalities: Because of the possibility of multimodality, the characteristics of the input modalities are not mutually exclusive. Multimodality is defined as an interaction that can include multiple input modalities at the same time, such as voice and gestures. The analysis reveals that there are numerous input opportunities. The most common are voice, touch, and gestures. ***Voice input*** [11, 25, 26, 30, 38, 39, 47, 49, 50, 51, 55, 56, 57, 58, 59, 60] can be command-based or natural language processing (NLP) [56]. ***Touch interaction*** [39, 46, 48, 51, 53, 56, 57, 59, 60, 61] can include both near and far touch. Near touch in this context refers to directly touching the interaction trigger, whereas far touch refers to a mapping of the touch interaction, i.e., ray-casting on a distant object [56]. Near touch interaction can take the form of giving input via a virtual keyboard while wearing an HMD [39] or simply touching buttons [60, 61]. McGill et al. [46] provide another example of near touch interaction. The authors describe an AR solution in which 3D content is attached and mapped onto the body, in this case around the user's wrist. ***Gestures*** [11, 25, 26, 27, 29, 30, 38, 42, 47, 48, 50, 51, 52, 53, 55, 56, 57, 58, 59, 60, 62, 63] are the most commonly used AR input modality and include gestures using fingers, hands, arms or the entire body. They are widely used regardless of hardware, but tracking mechanisms are required to detect the gestures. ***Free body movement*** [11, 24, 58] in the environment, such as the user's position, can be used as input as an alternative to gestures. In some cases, such as the HoloLens 1 cursor, the line of ***gaze*** [11, 30, 46, 51, 55, 58] also serves as an input. Aside from active user inputs, ***sensors*** [11, 11, 23, 30, 53, 55, 57, 60, 61] can provide autonomous input. Internal or external sensors can be used. Some examples are infrared cameras, acceleration sensors and gyroscopes, other telemetry sensors, GPS, Bluetooth, or RFID. Gyroscopes, for example, are also used to detect and record head movement and position. With the help of GPS, it is possible to track the user's location. Sensor combinations are also possible in this case. Furthermore, tracking ***eye movement and blinks*** [30, 46, 55, 56] can be used as inputs. Inputs can also be ***video or image*** data [11, 29, 30, 43, 53, 55, 56, 60, 61]. Cameras are used to take photos or videos for further analysis. QR code or barcode readers are common, particularly in industrial settings. The ***brain-computer interface (BCI)*** [32] is an emerging input technology in which brain activities are measured and used as inputs. In addition, ***generic input devices*** [11, 24, 27, 30, 39, 44, 45, 46, 51, 52, 54, 55, 56, 56, 58, 62] are mentioned, which allow for other types of user input. Scanning gloves, handheld clickers, foot pedals, and traditional input devices are examples of these. External tracking hardware, such as cameras for tracking hand localization, is also described.

In general, the inputs mentioned above can be used as predictive features. Thus, it is possible to predict what a user will do next, for example, by analyzing eye movements. Therefore particular objects may come into focus and become more likely for a subsequent interaction. As previously stated, input modalities do not need to be mutually exclusive because multiple inputs can be addressed simultaneously. Furthermore, specific sequences of input modalities occur frequently together. For example, as with HoloLens 1, gaze-then-gesture can be used in combination [39].

D_4 Output modalities: This dimension defines an interaction's output, which can be haptic, visual, auditory, or a combination of these. ***Haptic feedback*** [27, 34, 45] can be active or passive and can be provided by an additional haptic glove. The most described characteristic is ***visual feedback*** [9, 14, 26, 27, 28, 30, 31, 31, 33, 36, 37, 40, 41, 43, 51, 52, 53, 55, 57, 60, 61, 62, 63, 64, 65, 66], which includes any form of visual presented information as an output from an interaction. The final output characteristic is ***auditory feedback*** [36, 37, 61, 66], which refers to audio feedback from the interaction. Output modalities, like input modalities, are not mutually exclusive and can be combined.

D_5 Interaction implementation: Interaction can be divided into three main task purposes, independent of the information the user aims to interact with. The goal of an interaction can be ***virtual object selection*** [9, 11, 26, 27, 28, 30, 31, 33, 35, 36, 37, 38, 40, 41, 44, 50, 51, 55, 57, 60, 61, 63, 64]. Object selection is mostly always the first step in a sequence of interactions. Because AR combines virtuality and reality, the interaction can also include ***physical object selection*** [36, 37, 51]. Following selection, ***virtual object manipulation*** [11, 24, 27, 29, 33, 40, 44, 48, 50, 51, 53, 63, 64, 67] is common, which can be, for example, in the form of picking, dropping, dragging, rotating, or zooming.

D_6 Interactivity relation: The dimension interactivity relation classifies interaction as digital, physical, or human. This dimension is independent of the specific use case scenario and the information. We define ***digital objects*** [15, 31, 34, 54, 59, 62, 67] as only virtual objects in AR that the user can interact with. Additionally, this can include smart objects and IoT data. Interactions can also occur with ***physical objects*** [11, 14, 24, 26, 27, 33, 34, 38, 43, 53, 59, 62, 65, 66, 68, 69]. I.e., the users interact with their immediate physical surroundings, and the AR solution serves as a mediator between the user and the real world. Tangibles are one example of this. Despite the interaction with objects, face-to-face interactions with other ***people*** [24, 33, 47, 59], such as co-workers, are possible when using an AR solution. This can be face-to-face interaction in reality, as AR allows for the simultaneous perception of reality and virtuality, or virtual interactions with other people, such as video calls.

D_7 Sequence of interactions: This dimension describes how a sequence of multiple interactions can be designed. This sequence may include various input modalities and interaction implementations. Interactions can be classified according to their ***frequency*** [34], ***duration*** [11, 34, 68] or speed, ***variety*** [34], and ***concurrency*** [11].

5. Discussion

The paper's goal was to create a taxonomy to aid scholars and practitioners in developing a shared understanding of AR interactions. We are convinced that when designing new AR applications, the choice of interactions is not trivial. With the help of this taxonomy, users can achieve guidance in terms of the variety of interaction patterns and consider all possibilities during new design and development. We have shown a wide range of dimensions and characteristics. Our taxonomy is independent of application domains because it focuses on individual atomic interactions rather than AR solutions and their context. This also means that we do not focus on the purpose of the interaction, such as collaboration, documentation, or process support, because these tasks can also be mapped on single interactions and are not unique in their interaction patterns. When it came to input modalities, we discovered ten characteristics in particular. This large number of modalities reflects the technological advancement and the increasing applicability of hardware. Touch interfaces and precise tracking technologies, for example, are now state-of-the-art but were not so easily accessible a decade ago. As a result, the complexity of input modalities increases further because the dimension does not meet the criterion of mutual exclusiveness proposed by Nickerson et al. [13]. The reason for dropping this criterion is that while AR solutions can use a single input modality to fulfill a task, most AR solutions use multiple input modalities to enhance the perception and usefulness of the augmentation. Consequently, the combination of modalities is becoming more common in recent papers as technological capabilities improve. This means that it is not necessary to choose only one input modality for service design but that a combination is indeed possible and reasonable. The same effect is visible in output modalities, which are also combined in AR solutions.

Following the technological advancement, it is apparent that the hardware dimension defines features such as the possibility of hands-free interaction. Consequently, understanding the use case of an AR solution is crucial for selecting appropriate hardware.

Surprisingly, collaboration within AR is only scarcely addressed by research. Only three papers deal with interactions with co-workers, and two emphasize the ability to collaborate locally. This limited collaboration is also mirrored in *D_1 Users per device*, with only two papers proposing interactions for multiple users per AR device. This demonstrates that, until now, there has been a focus on single-user settings for AR solutions. Osterbrink et al. [4] have shown, for example, that collaboration with co-workers is a necessary requirement for AR applications in safety-critical environments. Another noteworthy aspect is *D_7 sequence of interactions*, which is only covered by three papers, none of which address every characteristic. Thus, one reason for this is that core HCI literature, in particular, is more focused on specific facets of interactions, and therefore dealing with a fine-grained interaction is plausible. This reliance on single interactions in IS literature is surprising and opens up a broad field of research opportunities.

6. Conclusion

In this paper, we systematically created a taxonomy to conceptualize the interactions of AR solutions. The provided taxonomy has seven dimensions and 29 characteristics, and it serves as a tool for researchers and practitioners by supporting a systematic analysis of interactions in AR solutions. To the best of our knowledge, this is the first attempt in IS to systematize this domain. Despite analytical support, the taxonomy can guide the design of AR solutions because the solution space is described comprehensively. As a result, practitioners can use it to determine whether an AR solution is feasible for the business's needs.

Despite the taxonomy's thorough development, the paper has some limitations. Firstly, regarding the breadths of the literature review: we decided to concentrate on a wide range of IS literature and solely add core HCI journals. A broader range of HCI literature could have expanded the taxonomy's foundation. Still, as we met the ending conditions proposed by Nickerson et al. [13], we are convinced that the resulting taxonomy is exhaustive.

The taxonomy reveals potentials for future research. Because the literature is primarily focused on single interactions, researchers may revisit the issue of multimodality and investigate best practices and advantageous combinations for input and output modalities and patterns. This may, for example, be manifested by introducing archetypes of interaction patterns. Moreover, the collaborative aspect of AR is frequently understudied in literature, resulting in unrealized potentials for AR. For these reasons, we want to encourage researchers to investigate this field further.

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