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An interdisciplinary Co-authorship networking perspective on AR and human behavior: Taking stock and moving ahead

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A R T I C L E I N F O

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A B S T R A C T

The field of augmented reality (AR) and human behavior emerged when Azuma et al. (2001) refined the term *augmented reality* in 2001. Research on the topic has grown steadily in the past decade, yet there is a notable lack of consensus on humans' motivations and outcomes in interacting with AR. The present research takes a bibliographic approach to shed light on current research on AR in human-computer interaction and, using topic modeling, to identify and classify the topics that have drawn researchers' interest. The results reveal three major topics of interest to researchers, namely "Education, Learning & Training Research", "Marketing, Consumer Behavior & Business Research", and "Digital Tourism & Cultural Heritage Research". Drawing upon co-authorship theory, we identify prominent AR expert co-authorship networks that work on similar topics, yet also highlight that AR research is concentrated in a few research groups that publish articles with similar groups of authors and little outside their own networks. Together with AR experts from the four largest co-authorship networks, we highlight the common challenges that emerge in AR research, suggest solutions, and jointly propose a research agenda for AR and human behavior research.

1. Introduction

Defined as a technology that overlays realistic digital content on the physical environment in real-time (Azuma et al., 2001), augmented reality (AR) is widely hailed by practitioners and technology providers as an emerging technology that will significantly affect how humans experience - and interact with-digital content in their daily lives. TECHNAVIO (2022) reported a 38% growth in the global AR industry in 2020 alone and predicts a further $76.99 billion in growth by 2024. Considering AR's potential applications across a wide range of industries, including tourism, retail, marketing, healthcare, entertainment, and education, AR has also captured the interest of academic researchers in various disciplines, such as psychology, computer science, social sciences and arts and humanities. For example, various studies describe AR as a powerful tool for improved efficiency and effectiveness in work-related tasks (e.g., AR for team collaboration, AR-assisted

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manufacturing, AR employee training) (He et al., 2017; Reif and Günthner, 2009), in healthcare settings (AR-assisted surgery, AR therapy to reduce phobia, AR for rehabilitation) (Alamri et al., 2010; Sielhorst et al., 2008), and in marketing. Here, the use of AR is intended to contribute to numerous marketing objectives, such as increasing consumer engagement, aiding consumer decision-making, stimulating a positive customer experience, or improving marketing-relevant outcomes, such as customer loyalty and sales (Carrozzi et al., 2019; Chylinski et al., 2020; Heller et al., 2021; Hilken et al., 2020; Jessen et al., 2020; Rauschnabel Babin, et al., 2022).

Despite the growing use of AR in diverse contexts and the related proliferation of theoretical insights into human-computer interaction with AR (e.g., based on technology acceptance models, situated cognition, or value creation), there is a notable lack of consensus on humans' motivations and outcomes in interacting with AR (de Ruyter et al., 2020; Hilken et al., 2020). In addition, academic research within various disciplines conceptualizes AR differently, with competing definitions of the term and, often, even a conceptual overlap with related yet distinct technologies, such as virtual reality (VR) and artificial intelligence (AI). For example, some researchers do not differentiate between AR and VR, while others consider AR a "distinct type of VR" (Wedel et al., 2020, p.443), and still others distinguish between several types of AR (e.g., head-worn vs. handheld) and VR (interactive 360° video vs. VR that allows users to walk around in a virtual space). Others claim that AR and VR are fundamentally different concepts that should be separated (Rauschnabel, Felix, et al., 2022). These inter- and cross-disciplinary differences potentially engender misunderstandings about what AR entails and how it affects human-computer interactions and subsequent human behavior.

As in other emerging research fields, several strong AR research groups (as demonstrated by joint authorship) have emerged in the past decade. While these expert groups are at the forefront of research related to AR and human behavior, they tend to focus on specific topics or application contexts, such as technology acceptance (Rauschnabel et al., 2018; Rese et al., 2017; Baier, Rese, & Schreiber, 2016), AR in tourism (Tom dieck et al., 2018; Jung et al., 2016; Orús et al., 2021), and AR in consumer decision-making (Heller et al., 2019a, 2019b; Hilken et al., 2018). As a result, these and other experts seem to generally work within their own research clusters, and the authors evidently rarely collaborate for publications outside their co-authorship networks. This poses the risk of missed opportunities for knowledge sharing, learning, and collaboration across research networks (and, thus, across disciplines). Consequently, while research proliferates as shown by the number of AR publications (see Fig. 2), it may remain constrained within fixed groups of co-authors, with large distances between co-authorship networks.

This siloed structure of AR research, though perhaps reflecting a natural development in any emerging research field, threatens to reduce overall research effectiveness and efficiency by constricting knowledge exchange (Friedman & Friedman, 2018). Furthermore, because the growth of AR is largely reliant on advances in software and hardware, the computer science discipline has taken a leading role in AR research. When we look at research beyond that discipline, however, we find scattered research networks with only a few researchers co-authoring publications (Fig. 6), this clearly demonstrates the need to map the key research networks on human-computer interaction with AR, to highlight potential (missed) opportunities for collaboration, and to encourage authors to collaborate more broadly to advance the overall research field. Complementing the work of (Friedman & Friedman, 2018), the overall aim of this article is to encourage interdisciplinary work and collaboration across research networks and clusters. In pursuit of that goal, we address the following research questions.

RQ1 Which co-authorship networks drive AR research involving human behavior?

RQ2 What topics emerge in research merging human behavior and AR?

RQ3 Is AR research concentrated within a few co-authorship networks?

First, we examine the state of AR research in various disciplines over the past 20 years, determine how the contributions by discipline evolved in that period, and identify how research efforts among expert co-authorship networks (measured by publications) have been distributed to date. Second, we highlight how distinct author groups may have developed centers or hubs of AR research expertise, and we then look at whether and how these groups are interconnected. Third, based on their research interests, we offer AR researchers a roadmap for uniting their efforts to stimulate further research in this multidisciplinary field, a highly relevant aspiration in the time of the emerging "metaverse."

This study employed bibliometric methods to investigate the structure of AR-related research fields by mapping several types of data (e.g., co-authorship, author keywords, and textual content). Bibliometrics is defined as a set of statistical methods used to investigate and assess the evolution, structure, and dynamics of the sciences and their respective disciplines (Koseoglu et al., 2016). According to Benckendorff and Zehrer (2013), bibliometric methods can be grouped into two categories (i) evaluative techniques (e.g., productivity measures, impact metrics): and (ii) relational techniques (e.g., co-citation, co-authorship, co-word, and bibliographic coupling analysis). This research adopted the techniques of the second category to identify and analyze several types of relational networks.

2. Background

2.1. Augmented reality

AR is often seen as a forward-looking technology that will drive the digitization of society. AR enables people to access, process, create, and share digitally augmented visual content (Büyüközkan and Göçer, 2018). Such content can range from very simple (e.g., superimposed text information; assisted reality) to very realistic (e.g., well-integrated, interactive 3D objects; mixed reality). However, unlike previous interactive media, AR experiences are not necessarily limited to the size of a two-dimensional screen anymore. Users can view the content where it is most useful to them in the world (e.g., a virtual couch in its actual size in their living room, rather than a photo in an online catalog). AR experiences are hybrid since they include both physical and digital elements, which is the key difference from other concepts (Hilken et al., 2022a; Golf-Papez et al., 2022; Chylinski & Heller, 2022). For example, in virtual reality (VR), people are completely isolated from the environment and present in a synthetic, artificial world (Rauschnabel, Felix, et al., 2022).

In 1997, Ronald Azuma published a now classic work on AR where he discussed AR's unique characteristics, technological foundations, and summarized various use cases and proposed future research directions, including user research (Azuma, 1997). Four years later, Azuma et al. (2001) published an updated and complemented version of this initial article. We argue that these two highly cited articles serve as a prototypical "game changer" in the discipline, leading to increased publications in the following years. Research on AR has gained traction in various disciplines, with a focus on studying human-computer interactions (Javornik et al., 2022; Rauschnabel et al., 2022). Specifically, AR's ability to create virtual objects that augment human interaction with the physical world has drawn the interest of researchers in the fields of marketing research and services research (Carrozzi et al., 2019; Chylinski et al., 2020; de Ruyter et al., 2020; Heller et al., 2021; Rauschnabel et al., 2017), the health sciences (Kaczmarek et al., 2017; Kogan et al., 2017; Ng et al., 2019), psychology (Botella et al., 2010 Juan et al., 2006), engineering management (Schein & Rauschnabel, 2021), education (Cai et al., 2014; Gutiérrez and Fernández, 2014), and tourism (tom Dieck et al., 2018; Jung et al., 2016). Computers in Human Behavior has established itself as a leading journal for AR research, with

354 publications on the topic over 20 years (2001–2021). Given the vast amount of available research and the increasing attention that AR has received since 2016 (seemingly provoked by the famous game Pokémon Go), we seek to uncover and highlight the various AR expert co-authorship networks that have had the greatest impact on the discipline of AR and human-computer interaction.

2.1.1. Research collaboration and authorship networks

Collaborative research is believed to produce a greater research impact than a solitary researcher's work in terms of number of publications (Katz & Martin, 1997; Lee & Bozeman, 2005), an obvious explanation being that an individual researcher lacks the personnel and resources that author teams enjoy. From a theoretical perspective, social capital theory contends that collaborative research produces a greater impact because research networks can share resources, such as physical equipment and financial resources, as well as knowledge resources, such as expertise and ideas, while also distributing the workload among multiple authors (Lee & Bozeman, 2005). Furthermore, research collaborations and the resulting authorship networks provide authors with social support and facilitate knowledge transfer (Li et al., 2013). Co-authorship has been described as the explicit product of scientific cooperation (He et al., 2011). Every time a researcher publishes a co-authored piece, a personal co-authorship network is established. The co-authorship of an article represents the academics who contributed directly to its content and illustrates the one-to-many connections between individual researchers and their co-authors. When individual co-authorship networks are connected based on the co-authors' cumulative production (in a research area), they create a larger network that is the sum of the individual co-authorships (Ding, 2011; Liu et al., 2005). When the same group of authors repeatedly engages in co-authorship, we refer to it as an expert group or expert network. Detecting such expert networks is relevant to identifying experts, evaluating scientific research publications, addressing relevant challenges, and seeking research partners to promote further research in a given field.

3. Methodology to take stock

To identify AR expert co-authorship networks, we collected publications systematically, combining bibliometric methods with text mining approaches (Blei et al., 2003; Chen et al., 2020) to garner insights into the topical landscape of the collected publications.

3.1. Data collection

To obtain the corpus of literature, we defined a search string and searched two academic databases commonly used for systematic literature reviews: Web of Science and Scopus. The search encompassed all academic articles published in English from 2001 through 2021. We chose 2001 as the starting year, as it saw the publication of what is widely regarded as the seminal work on human-computer interaction in AR (Azuma et al., 2001) and because there was literally no research activity prior to that year. The keyword search focused on the topics of articles (title, abstract, keywords) and comprised keywords related to AR technology, including "augmented reality," "mixed reality," "extended reality," and "enhanced reality." These keywords were combined with a second string containing the keywords "consumer," "user," "tourists," and "visitor" to capture research focused on human-computer interactions. To capture the broadest scope of literature, we did not limit the search to any specific discipline. The initial corpus comprised 6407 references (2423 from Web of Science and 3984 from Scopus).

Next, we refined the initial corpus using the multiphase exclusion process illustrated in Fig. 1. We first merged the two datasets and excluded duplicates (2,039) and some articles that were outside the timespan of our corpus (41). Subsequently, we screened all the remaining titles and abstracts and removed manuscripts if (a) the research discipline was not reported, (b) the title and abstract indicated that the focus of the article was not AR, (c) no keywords were provided, (d) the article lacked an abstract, (e) author names were not provided, (f) the article was not in English, or (g) the article was a lecture note or a contribution to a conference proceedings.

In a third step, to focus on the relevant research areas for computers in human behavior, we selected only articles that addressed the research areas of *Computers in Human Behavior*. To ensure that our network and text analyses covered the publications most relevant to our research objectives, we filtered the documents based on these research areas, retaining only those articles that related to at least one research field in business, economics, or the social sciences or to fields associated with the journal *Computers in Human Behavior*. Furthermore, the research areas *business, management and accounting; business and economics*; and *economics, econometrics and finance* are collectively grouped as *business, management, and economics*, while the fields *social sciences–other topics* and *social sciences* are joined under the term *social sciences*. This filtering step reduced the dataset to 2612 publications. To ensure that we captured the leading AR expert co-authorship networks, we also employed a journal quality filter and selected only the top 50% of journals on the basis of either the Scientific Journal Rankings (SJR) or Journal Citation Reports (JCR) quality indicators, as these are the two most common ranking criteria for journals across various disciplines (Ciuchita et al., 2022). If both indicators were available for one journal, the journal was included if it was in the top 50% of at least one of the indicators. Some journals are only indexed in either the SJR or JCR ranking, for these journals the publication was excluded if the journal was not in the top 50% of that quality indicator. The final corpus for analysis consisted of 1348 articles.

3.2. Data analysis

3.2.1. Development of the field

Fig. 2 depicts the publication trend by the total number of publications. It shows that research on AR steadily increased from 2006 onward and then dropped slightly in 2016 before rising exponentially in the last four years. In 2021, a total of 254 documents were published, revealing that the main body of research on AR was published in recent years.

The growth in total number of publications (Fig. 2) is accompanied by a more diversified distribution of publications among the selected research areas (see Fig. 3).[1] While AR-related research appears to have been dominated by the computer science field until 2004, interest in this technology has grown considerably in other research areas in the past 15 years. Disciplines such as arts and humanities; business, management, and economics; psychology; and social sciences have increased their share of the number of publications.

3.2.2. Co-occurrence of research areas

Before focusing on the three proposed research questions, we start with a broad overview of AR research. This section describes the connections found among the selected publications by computing the frequency of co-occurrence in the research disciplines (Yan & Ding, 2012), which we visualize using bibliometric relational techniques. Based on the visualization, we infer an increasing relevance of AR-related research in economics and business disciplines.

As discussed in section 2.1, AR research has increasingly been conducted in disciplines outside computer science in the past two decades, producing a more diversified distribution of publications across our focal disciplines. Fig. 4 provides further insights into the relational structure among these disciplines by mapping their co-occurrences in a network. In this visualization, the node size corresponds to the node degree (i.e., the total number of linkages of a node), and the edge color reflects the frequency of co-occurrence (the darker the color, the greater

[1] A publication that relates to two or more research areas simultaneously is counted twice in Fig. 3.

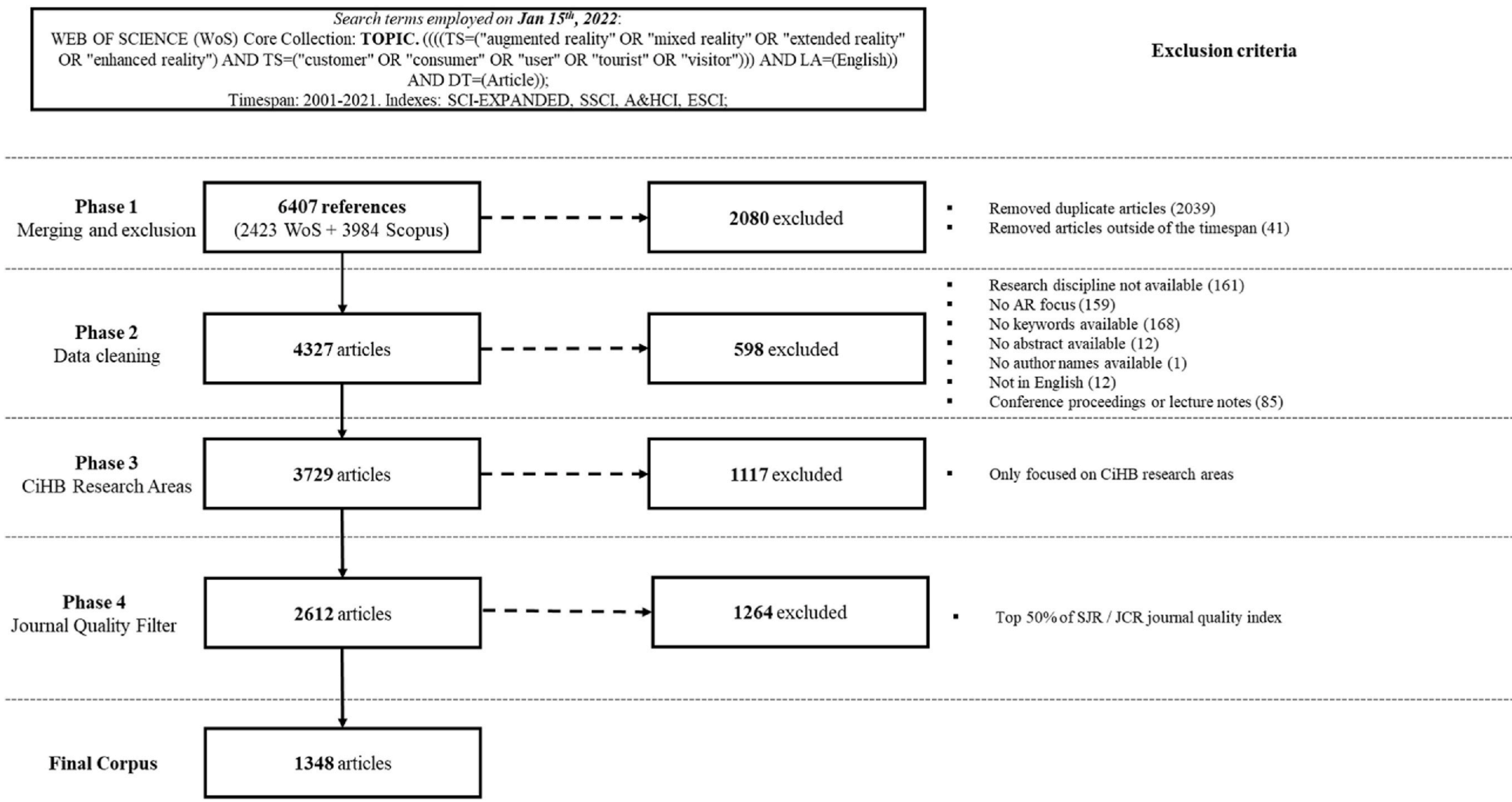

Fig. 1. The exclusion process of the AR studies.

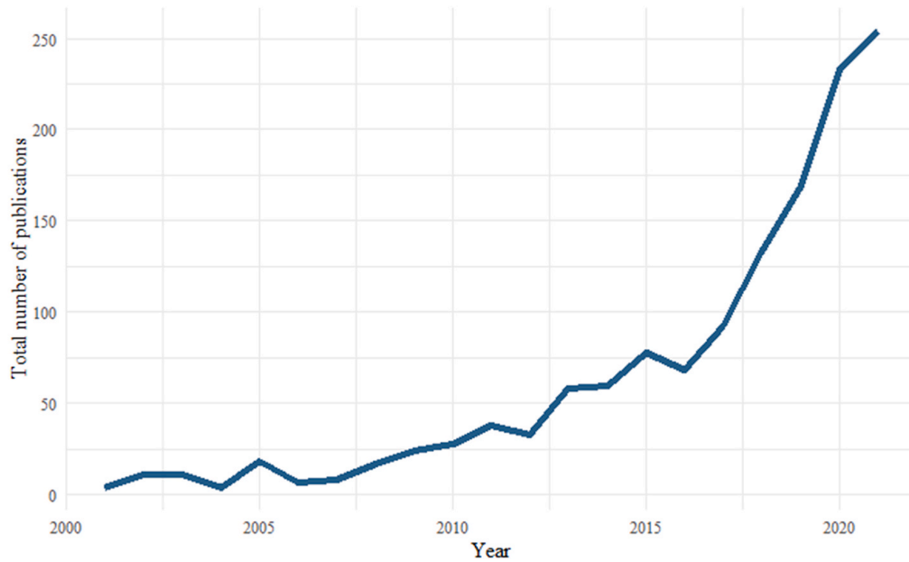

Fig. 2. Total number of publications over time.

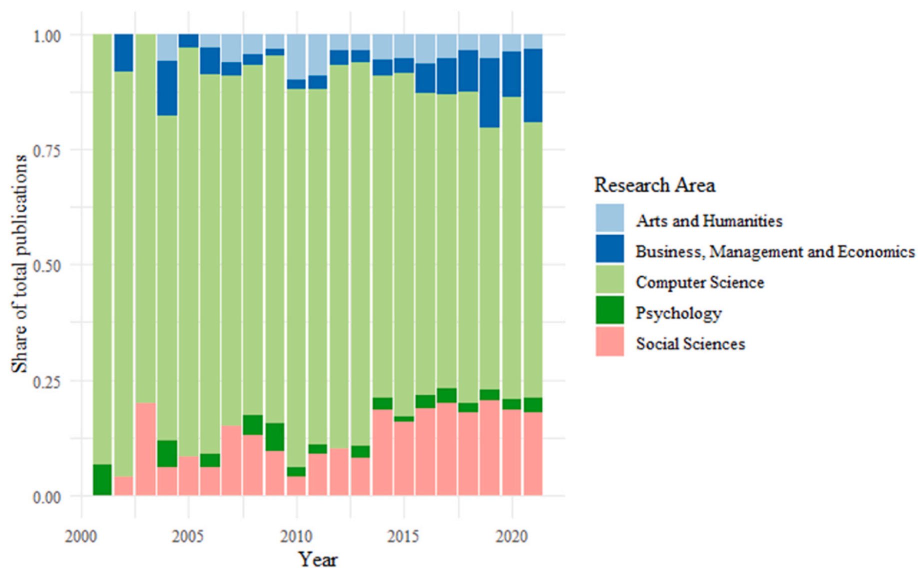

Fig. 3. Share of total publications among research areas.

the frequency). The disciplines related to business, economics, and the social sciences as well as those associated with *Computers in Human Behavior* are highlighted in the same colors as in Fig. 3.

The co-occurrence network indicates that the disciplines of computer science, business, management and economics, engineering, and, to a certain extent, the social sciences take central positions in the network, and each links to numerous other research areas. While the centrality of computer science and engineering comes as no surprise, the high degree of centrality in business, management, and economics reflects AR technologies' growing importance in business-related studies.

3.2.3. Topic modeling

We employed topic modeling to find the underlying topics in the abstracts of the literature corpus and to detect salient, meaningful patterns in the AR research landscape. Topic modeling is an unsupervised machine learning technique for text mining and, hence, does not require any prior classification by human coders (Hopp et al., 2018). Instead, based on the wording of the documents' texts, it identifies latent topics and thematic structures through statistical procedures. In general, such procedures are based on the assumptions that documents have latent semantic structures (i.e., topics), that these structures can be inferred from the co-occurrences of words within the documents, and that this inference can be simulated algorithmically. Beta values represent word-topic probabilities, i.e., the probability of a term being generated from a particular topic. In other words, the beta values can be interpreted as an indication of how common a particular word is within a topic (Hopp et al., 2018).

In the subsequent analysis, we relied on the widely used Latent Dirichlet Allocation (LDA) algorithm developed by Blei et al. (2003). LDA represents documents (in our case, publication abstracts combined with the publication titles) as bundles of topics and defines each topic by a word vector and each document by a topic distribution. In other words, a unique topic profile is determined for each abstract that indicates the probability that the topics identified in the entire corpus appear in that abstract. As in the topic distribution of each document, each topic can be identified by a distribution of words. Hence, in addition to the topic profile of each article, the set of words used to define the respective topics is extracted.

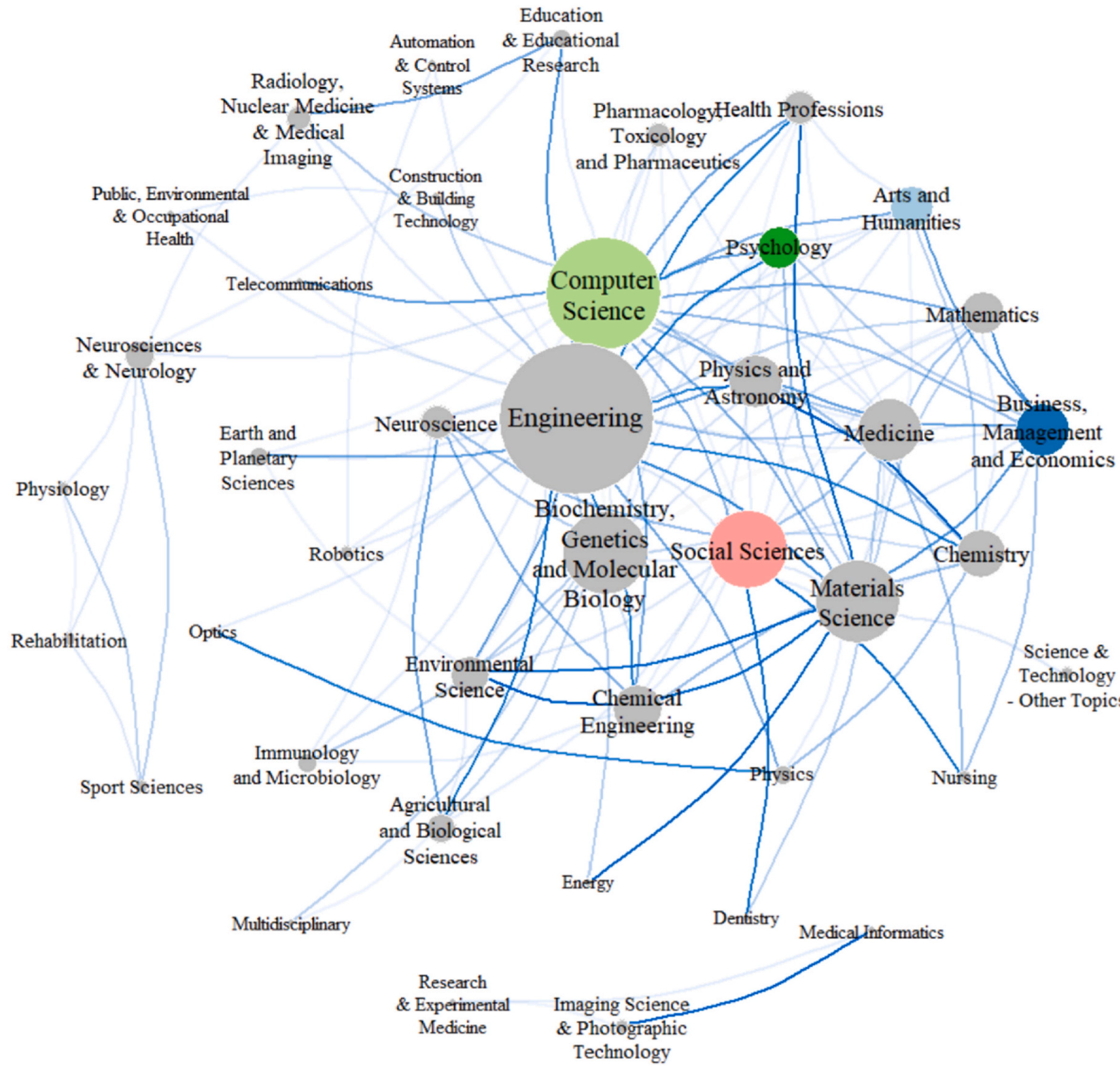

Fig. 4. Research disciplines co-occurrence network.

3.2.4. *Topic detection and topic activity index (TAI)*

Table 1 summarizes the results of the topic modeling. The first column indicates the topic number, and the second defines its label. As the LDA algorithm derives topics only in statistical terms without providing meaningful labels (Blei, 2012), the actual labeling of the topics is done through human intervention. To support the manual labeling, the 10 words with the highest per-topic-per-word probabilities, labeled β, are listed in column three of Table 1 (with the associated β values in the last column). Based on the topic distribution per document computed by LDA, we associate each publication with a single topic by assigning the topic with the highest probability (labeled gamma). As discussed below, highly technical publications related to computer science are excluded from the topic modeling process. Consequently, the remaining publications are equally distributed across the three detected topics and comprise between 84 and 105 publications each.

We used the results of the topic modeling to compute the topic activity index (TAI) per author. While most authors exhibit a high TAI for one specific topic, some contribute to a greater or lesser extent to multiple topics (see Fig. 5). This shows that most authors (70.4.1%) contribute to only one of the three identified topics, while some (27.2%) contribute to two topics, and only very few have co-authored publications on three topics (2.5%). For example, Tseng-Lung Huang and Philipp Rauschnabel are among the authors in the sample who contribute to all three topics, while several authors, including Mathew Chylinski, Ko de Ruyter, and Dominik Mahr, contribute to two distinct topics. Hence, rather than focusing on a single topic within the AR research landscape, these authors exhibit a relatively high degree of multidisciplinarity. However, Fig. 5 also highlights that most authors work only on one topic as identified via the TAI, highlighting a stronger need for interdisciplinarity in AR research.

Additional preprocessing steps were required to prepare the corpus as an input for the LDA algorithm. First, because we focus on human-computer interaction research, we excluded highly technical publications related to the research area of computer science from the topic modeling analysis, leaving 288 publications. Next, following the common approach in text mining applications, the texts were converted to lowercase, contractions were replaced, numbers, dates, time indications, and punctuation were removed, and to address the presence of word variations within the texts, words were reduced to their stems. In addition, common English stop words and a list of custom stop words (e.g., "augmented," "reality," "customer," or "introduction", "methodology", or "conclusion") were removed. The reason to exclude custom stop words is that these words either were part of the initial search string in the databases that served as a starting point for the corpus, or that these appear regularly in academic publications. Third, following the suggestion of Blei and Lafferty (2009) and using the approach suggested by

Table 1
Topics, topic labels, and the 10 most important keywords based on their betas.

Topic number	Topic label	Keyword	Beta
1 (84 publications) Light-blue square	Education, Learning & Training Research	learn	.034
		student	.029
		task	.026
		simul	.022
		instruct	.010
		head	.010
		assist	.010
		teach	.009
		construct	.008
		scene	.008
2 (105 publications) Dark-blue circle	Marketing, Consumer Behavior & Business Research	retail	.041
		product	.034
		custom	.033
		onlin	.029
		app	.024
		brand	.020
		purchas	.018
		servic	.013
		smart	.013
		flow	.011
3 (97 publications) Green triangle	Digital Tourism & Cultural Heritage Research	tourism	.026
		game	.021
		visitor	.020
		cultur	.018
		heritag	.017
		digit	.017
		map	.016
		museum	.016
		tourist	.015
		motiv	.010

Hopp et al. (2018), the vocabulary for the topic modeling algorithm was pruned by omitting words with low discriminatory power based on their term frequency–inverse document frequency (tf-idf) values. Specifically, words with an average tf-idf value in the bottom 35% were removed from the dataset before the final analysis.

To determine the appropriate number of latent topics within the corpus, we computed the topic density of the LDA model for different numbers of topics. Employing the principle of the maximization of information divergence (Deveaud et al., 2014) between topics as well as human judgment in interpreting the discovered topics, we identified three distinct topics that characterize the AR research landscape.

3.2.5. *Topic activity index*

To analyze and map the AR research landscape, including individual authors' contributions to the research community, we adapted Chen and Xiao (2016) keyword activity index (KAI), defined as the ratio between an institution's share in publications containing a specific keyword and that institution's share in all publications. In other words, the KAI measures whether a research institution focuses on a given research topic, which is assumed to be represented by publication keywords. Rather than considering research institutions as the unit of analysis, we focused on individual authors, but establishing a KAI on the author level is likely to produce meaningless findings, as the number of author-specified publication keywords has increased significantly in recent years together with their diversity. To evade this pitfall, we adapted the KAI and computed a TAI using the results of our topic modeling. More precisely, using the detected topics, we calculated a TAI for each author in the dataset as follows:

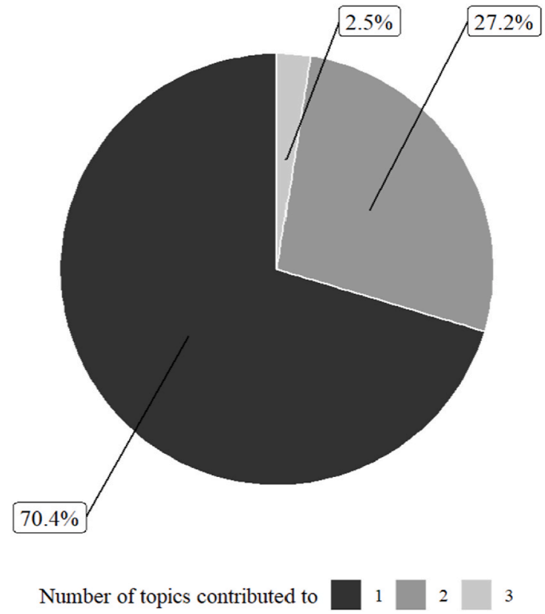

Fig. 5. Number of topics contributed to by share of authors (percentage).

In formula 1, the numerator is obtained by dividing each author's number of publications associated with a specific topic by the total number of publications associated with this topic by all authors. The denominator is calculated as the ratio between each author's total number of publications and the total number of publications by all authors (Chen and Xiao, 2016). Calculating the TAI allows us to classify authors according to a shared research focus and determine each author's extent of contribution to that research topic.

3.2.6. *Co-authorship network*

Relational bibliometric methods enable us to answer questions about the intellectual, social, and conceptual structure of sciences and/or disciplines (Koseoglu et al., 2016). This subsection visualizes and analyzes the co-authorship network of AR-related research to determine its structural characteristics. Co-authorship represents "one of the most tangible and well-documented forms of scientific collaboration. Almost every aspect of scientific collaboration networks can be reliably tracked by analyzing co-authorship networks by bibliometric methods" (Glänzel and Schubert, 2004). Thus, revealing co-authorship networks and identifying the relationships of coauthors (based on shared publications) provides value to the field. To model co-authorship networks, we apply additional preprocessing steps to ensure that the resulting network comprises co-authorships that are highly invested in the field of AR and its applications in various domains.

(i) Each author must have at least two publications in the present sample to be considered an AR expert.
(ii) We aim to distinguish groups of co-authors who frequently collaborate on research in the field of AR from individual authors who generally work on their own or in networks with varying authors (<2 shared publications with the same co-authorship network). Consequently, we exclude the latter individuals from the network and list them separately (see Table 2).

$$TAI = \textit{share of the author in publications associated with a given topic} / \textit{share of the author in all publications} \quad [1]$$

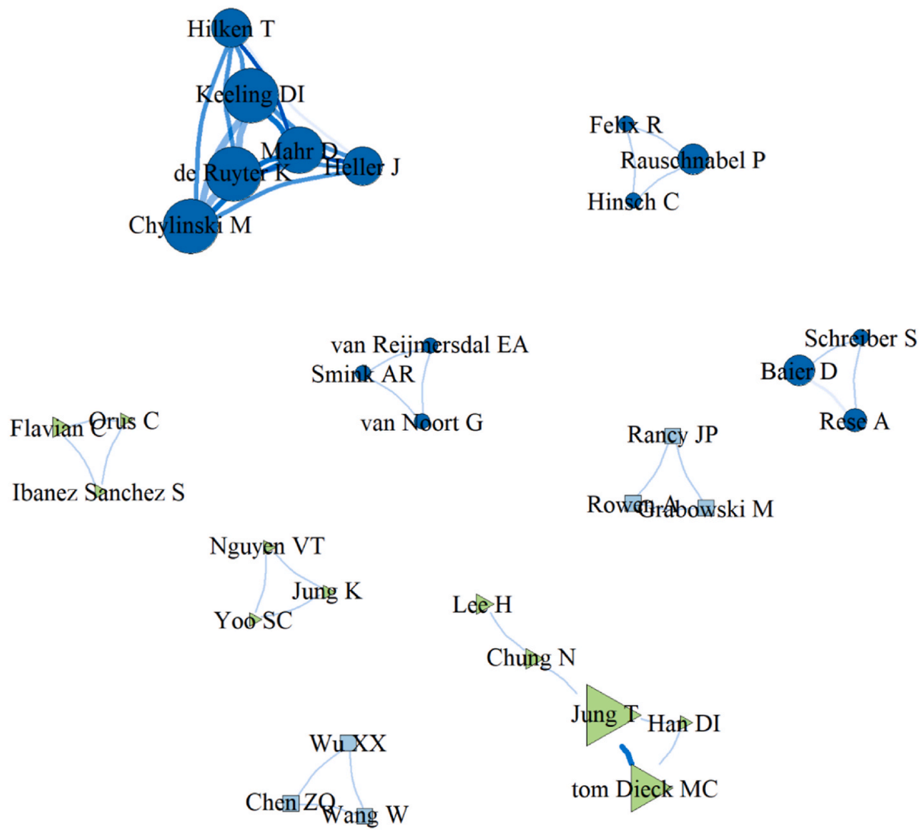

Fig. 6. AR expert co-authorship network.

Table 2
Individual AR expert authors.

Author	Number of publications	Highest TAI
Huang, T. L.	7	Topic 2: 2.724
Javornik, A.	6	Topic 2: 2.724
Gabbard, J. L.	3	Topic 1: 2.270
Park, S.	3	Topic 1: 1.135

(iii) To confirm that the co-authorships occur on a frequent basis, we filter out any co-authorship that appears only once in the sample. In other words, each group of co-authors must have contributed to at least two co-authored publications.

We retain only groups of co-authors including at least three authors. Given the scope of this article - the identification of co-authorship networks - we excluded several authors who qualify as experts yet are not involved in repeated collaborative networks. These authors are presented in Table 2.

The resulting co-authorship network is depicted in Fig. 6. Each author is represented by a node, the color, and shape of which reflects the author's research focus (i.e., the topic to which the given author most contributes based on the TAI). Specifically, the authors contributing the most to topic 1 (Education, Learning & Training Research) are represented by a light blue square, those focusing on topic 2 (Marketing, Consumer Behavior & Business Research) by a dark blue circle, and those primarily researching topic 3 (Digital Tourism & Cultural Heritage Research) by a green triangle. In addition, the size of a node reflects the author's total number of publications (irrespective of the dominant topic). Furthermore, the edges of the nodes, which represent the linkages between authors, are colored and weighted according to the frequency of occurrence; the more often two authors collaborate on a publication, the darker and thicker is the link between them.

As apparent in the visualization, the network is fragmented into smaller groups consisting of frequently collaborating co-authors, with no linkages between these groups. Furthermore, taking into consideration the research focus of each author, the groups appear to be collectively focused on a particular topic, as all authors within a group contribute the most to the same topic as indicated by their TAI. It is noteworthy that most groups consist of three or four authors, the exception being the groups around Jung, T. (bottom right) and Mahr, D. (top left). The latter, including six co-authors, appears to be particularly invested in repeated collaboration in AR research, as the frequency of co-authorship (i.e., the thickness of edges), number of publications (i.e., size of nodes), and density within the group (i.e., number of edges) are greatest in that co-authorship network.

4. Looking ahead: an AR research agenda by experts

To identify commonalities and challenges within and across the AR expert co-authorship networks, we reached out to the authorship networks in our corpus and invited the authors to work on a joint research agenda and to compile a list of the challenges in AR research and proposed solutions to them. We reached out to all co-authorship networks in Fig. 6 and received contributions from a total of four research groups. Furthermore, we jointly developed research topics on which AR researchers could collaborate in the future to further emphasize collaborative, high-quality AR research that advances the field. Table 3 summarizes the AR expert co-authorship networks and identifies the authors, their universities, and the AR expert co-authorship networks' publications. The sizes of the four networks range from three to six authors; notably, only one network's authors are all affiliated with the same university (METODO group at University of Zaragoza), whereas the other three networks consist of authors at either two, three, or four universities. Three of the four networks collaborate across different continents, and 11 of the 16 authors are based in Europe (68.75%).

Table 3
AR expert co-authorship networks and their authors, universities, and publications.

AR network	Authors	Universities	Network publications	Top network publications[a]
Augmented ReseARch[b]	Hilken, T. Heller, J. Mahr, D. Chylinski, M, De Ruyter, K. Keeling, D.I.	Maastricht University (NL) University of New South Wales (AUS) King's College London (UK) The University of Sussex Business School (UK)	**7**	Hilken et al. (2017), Heller et al. (2019a), Heller et al. (2019b)
Creative AR/VR Hub[c]	Jung, T. Tom Dieck, M.C. Chung, N. Lee, H. Han, D.	Manchester Metropolitan University (UK) Kyung Hee University (KOR)	7	Jung et al. (2015), Tom dieck and jung, 2018, Tussyadiah et al. (2018)
METODO Group[d]	Flavián, C. Orus, C. Ibánez-Sáñchez, S.	University of Zaragoza (ESP)	2	Flavián et al. (2019), Orús et al. (2021)
BAMIT Group[e]	Rauschnabel, P. A. Hinsch, C. Felix, R.	Universität der Bundeswehr München (GER) Grand Valley State University (USA) University of Texas Rio Grande Valley (USA)	2	Rauschnabel et al. (2019), Hinsch et al. (2020)

[a] Based on citation count in August 2022 involving at least two co-authors of the network.
[b] https://www.augmented-research.com/.
[c] https://www.mmu.ac.uk/creativear/.
[d] https://www.researchgate.net/lab/METODO-Research-Group-Carlos-Flavian.
[e] No website available.

Table 4
AR expert co-authorship networks' collaboration benefits, research foci, challenges, and solutions.

AR network	Collaboration benefits	Current research focus	Challenges and solutions	Future research questions
Augmented ReseARch	- Idea generation and conceptual development of research frameworks - Distribution of research tasks across universities - Access to various laboratories and funding - Reaping the benefits of interdisciplinarity	- How AR can create shared realities that enhance the co-creation process - Mapping consumer characteristics that shape privacy concerns regarding AR - The role of AR in the Metaverse	Challenge: - Access to software development for experimental purposes Solution: - Develop case-based AR business models with industry collaborations to validate academic findings in the real-world context	- What is the effect of combining AR with other technologies (e.g., VR), and in which context does it improve the user experience? - What multisensory elements beyond visual and auditory stimuli affect the AR experience, and in which contexts do they add value? - How can AR promote well-being and lead to positive behavior (e.g., healthier lifestyles, donation behavior)?
Creative AR/VR Hub	- Multidisciplinary research perspectives (technological, economic, and sociocultural) - Cross-faculty and cross-cultural studies due to international collaborations	- What drives AR user adoption? - How does AR facilitate user engagement and experience? - How can AR improve educational and training experiences?	Challenge: - Lack of proven business models using AR Solution: - Develop case-based AR business models with industry collaborations to validate academic findings in the real-world context	- How is virtual information displayed? - How can virtual content be properly personalized for each user? - In which situations might AR not be an appropriate tool, making the decision process more difficult?
METODO Group[d]	- Multidisciplinary approaches resulting in rigorous studies - Multicultural studies - Access to field studies	- The impact of AR in online shopping environments - How does AR influence consumers' decision-making process? - What is the best way to display virtual information?	Challenge: - Data collection in real environments (field studies/experiments) and reliance on laboratory studies Solution: - Collaborations between industry and academia	- How to personalize virtual content for each user depending on user characteristics - What constitutes the dark side of AR? - When should AR not be used in decision-making?
BAMIT Group	- Inspiration and idea generation - Complementarity of competencies	- What do people do with AR? - What does AR do to people? - AR as part of the metaverse	Challenges: - Reliance on existing AR apps - High market turbulence and uncertainty - The discipline is driven by rumors and imprecise definitions (e.g., metaverse, XR) Solutions: - Emphasize the need for interdisciplinary research teams (e.g., computer scientists and behavioralists) - Focus on rigorous conceptual output	- What is the metaverse and its role in relation to AR technologies? - How are ethics considered when designing and using AR applications? - How and in which contexts is AR an effective marketing tool?

Table 4 summarizes the input from the four co-authorship networks as compiled by one of the lead researchers within an AR expert co-authorship network. In the following, we summarize the AR researchers' perceived benefits of collaboration in co-authorship networks and describe the challenges they face as well as potential solutions. We further propose an agenda for AR research in the field of computers and human behavior.

Regarding the *Collaboration benefits* within an AR expert co-authorship network, the interviewed networks indicated that effective research is supported by idea generation, finding inspiration when working in groups, and the ability to distribute research tasks (e.g., conceptualization, data collection, data analysis, write-up) across network participants or even across faculties. In addition, given the rapid evolution of technology topics, with new devices with additional features being released yearly, a multi-author perspective inspires researchers and motivates collaborating in AR expert co-authorship networks. In addition, the potential for collaboration across groups was mentioned as an enabler of certain research approaches, for example, field studies.

The *Current research focus* of the four AR expert co-authorship networks includes user or customer adoption as well as how AR influences user experiences. Various foci are mentioned in relation to the latter, specifically, how AR facilitates user engagement and co-creation and how it influences distinct contexts, such as educational and training experiences or retail and shopping environments. In addition, the research networks investigate which type of content should be displayed in a given environment and how that content is perceived by heterogeneous user groups. Some research networks have also begun to investigate customers' privacy concerns when interacting with AR (Lammerding et al., 2021).

With regard to *Challenges and solutions* in AR research, we identified a broad set of challenges faced by the various AR expert co-authorship networks. Business school-based research networks conducting business-related research (e.g., marketing, retailing, tourism) seem to struggle primarily with access to software development resources, often related to the challenge of relying on existing AR applications when conducting experiments or field studies. Some AR experts also mentioned a lack of proven business models as a challenge, highlighting difficulties that persist when conducting impactful field studies. Additionally, collaboration between industry and academia, which often benefits both sides when conducting field studies and provides insights for managers and policymakers, is described as a challenge, drawing attention to the fact that, in some regions, few companies or organizations work with AR. As potential solutions to these challenges, the respondents described a need for more interdisciplinary research as well as stronger collaborations between academia and industry, not only to promote field studies but also to develop case-based AR business models to validate findings for context-specific industries or companies.

For future research, we have jointly developed a research agenda that proposes collaborative, interdisciplinary research to break down the research silos in the field of AR. We present the research agenda in section 6.

5. Implications

For over a decade, the production of AR research employing various methodologies across disciplines has accelerated at an increasing pace (Fig. 2). The present research contributes to scholarship on this topic in several ways.

First, we shed light on the state of AR research over the past 20 years and show how publications in various disciplines have evolved. We find that AR research in various disciplines has steadily increased over the years and that, in relative terms, the social sciences have particularly gained traction. This is reflected in growing academic output from domains such as human-computer interaction, business, psychology, tourism, and service research. This shift, identified by our bibliometric analysis, is visualized in Fig. 3 and may be interpreted as a general transition from a focus on technical features toward the application of AR technology and the derived value for the user. This increase in the diversity of research disciplines is seen in other technologies, such as VR and robotics, and is often interpreted to indicate that the technology is becoming mature and ready for the end-user market (Chylinski & Heller, 2022; Hilken et al., 2022c).

Second, based on the corpus of literature that encompasses 20 years of AR research in various domains, we identify the prominent research topics as defined by keywords. These three research topics (Education, Learning & Training Research; Marketing, Consumer Behavior & Business Research; and Tourism, Cultural & Heritage Research) classify an otherwise fragmented list of topics. Detecting topics based on keywords contributes to identifying common work streams among AR co-authorship networks, which can promote collaboration across research groups.

Third, we identify and highlight the nine co-authorship networks that differ in size and foci of research topics. Our conceptualization of a co-authorship network defines a network as at least two authors with at least two publications together. Our chosen bibliometric approach is systematic and offers otherwise hidden empirical insights into the work of co-authorship networks. The identification of these networks reveals a tendency of networks to inhabit silos; by uncovering this tendency, however, we highlight the potential for greater cross-network collaboration, which promotes cross-faculty and cross-disciplinary research collaboration and, as noted earlier, drives academic output on a given topic.

Fourth, we reveal the perceived benefits of collaborating in productive AR expert co-authorship networks as well as challenges and proposed solutions, which can guide academics in promoting efficient research in the field of AR.

Finally, based on the input of four AR expert co-authorship networks, we provide a joint research agenda to inform and guide AR research in the field of human-computer interaction. This agenda aims to promote ethical, cross-disciplinary expert research that shows both the positive and negative sides of AR and its impact on human behavior. While the media hype that emerged in 2022 regarding the metaverse certainly drew attention to this topic, academics have also highlighted the potential dark side of this virtual ecosystem, to which AR is a gateway (Golf-Papez et al., 2022).

6. Future research and limitations

Jointly with four co-authorship networks, we develop a research agenda to foster AR research that promotes meaningful studies regarding technology and human behavior. A summary of proposed research questions can be found in Table 4, and in the following, we have classified the research questions along three future research themes.

The first theme is '*Vertical integration of AR research*' and tackles research questions that deal with AR and the exploration of additional, unexplored features of AR. For example, current research almost exclusively compares AR versus other media formats or focuses on visual aspects of AR. Further vertical integration means exploring additional senses, opening the field of multisensory AR research for further exploration. Within this scope, researchers could investigate whether different control modalities (e.g. touch vs. voice commands, see Heller et al., 2019b) impact human behavior, or explore how enriching the AR experience with additional sensory stimuli, such as scents, music, or temperature, alters the experience and human behavior. Also part of this research stream is the personalization of AR content, and whether the required additional effort to design such experience pays off for retailers or policymakers interested in service innovation, measured in a change of perceptions or behavior.

The second theme is '*Horizontal integration of AR research*' and should focus on the combination of AR with other technologies in user experiences. This would promote an increase in external validity as users are often presented with a choice to choose AR or another technology to achieve a certain task (e.g. product trial, previewing a travel destination), and research should investigate in which settings users will choose AR over another technology, or whether first using AR followed by, for example, VR, promotes a certain change in behavior. There is almost no current research that looks at combining AR with different technologies (one exception is Hilken et al., 2022), yet with the emergence of virtual ecosystems like the 'Metaverse', that theoretically can be accessed via AR, VR, or a traditional computer, research that focuses on horizontal integration of AR with other technologies is important.

The last theme is '*Virtual ecosystems'*, and this theme relates to all research that focuses on virtual ecosystems, the technologies such as AR that are used to access these ecosystems, potential dark sides, and ethical concerns that emerge regarding these ecosystems. In 2022 the term 'Metaverse', coined by the social network company 'Meta' spiked the interest in such ecosystems again, and while some research exists on earlier ideas of virtual ecosystems like "Second Life" or online gaming communities such as "World of Warcraft", the 'Metaverse' is an unexplored and inconsistently defined research field that requires researchers to explore it further (Dwivedi et al., 2022; Hilken et al., 2022b). Importantly, research needs to highlight the ethical dilemma that can be amplified in virtual ecosystems and guide policymakers in the ethical development and governance of such systems (Golf-Papez et al., 2022).

We note some limitations of our research in relation to the chosen corpus of literature and the methodological approach, which offers a basis for conducting further bibliometric research in the field of AR.

First, we focused on a limited timeframe of 2001–2021. While we are confident that we captured a reasonable sample, especially at the beginning of this timeframe, we were unable to include the vast amount of research that had already been published in 2022, as doing so would have changed how our co-authorship network was set up in our model. As shown in Fig. 2, the number of academic publications on AR has increased exponentially since 2016; thus, the number of co-authorship networks is likely to increase as well as change in composition. Further research should investigate the development of AR expert co-authorship networks to detect them and reduce the likelihood of silos in AR research so as to better open up opportunities for fruitful knowledge exchange.

Second, our chosen topic modeling approach presents the dominant topic per author, meaning the topic to which the individual author has contributed the most. However, this approach does not indicate whether an author contributed equally to two topics or whether an individual author produced interdisciplinary scholarship (i.e., on diverse topics as indicated by the publications the author is involved in). While a co-authorship network may signal interdisciplinarity if the co-authors within the network work predominantly on different topics, future research should consider taking an approach that assigns weights to an author's contribution based on the various topics published, providing a more granular result from the topic modeling. There are likely to be some valuable linkages that could be built across the disciplines.

Third, to collect a manageable sample and because of the nature of the topic (i.e., AR research in the context of human-computer interaction), we excluded computer science publications from the co-authorship network method. Future research could further explore the computer science domain or even compare and contrast differences between the research domains.

The number of topics was partly determined by informed human judgment, so changing the number would appreciably change the outputs with regard to topic distribution and the established TAI values. In addition, we limited our analysis to a static LDA, that is, not accounting for any changes in the topics and their prevalence over time. We applied the LDA to the abstracts because of their consistent structure and availability. However, the abstract contains only limited information regarding the content of a publication, so we risked missing a broader, more in-depth analysis (i.e., a higher number of topics). Finally, the results of LDA greatly depend on the input words, which we filtered using a tf-idf threshold. This was a subjective choice, and using a threshold of 0.5 instead of 0.4 may have altered the results. Our study calls for more research collaboration not only within co-authorship networks but especially across networks and across countries in the AR research community, which could yield more comparative studies and more field studies with diverse samples.

Data availability

Data will be made available on request.

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