SOCIAL GRAMMARS OF VIRTUALITY 2024

Inside a Year of Research: A report on Key Trends and Findings in Extended Reality Scholarship

Annenberg Extended Reality Lab
University of Pennsylvania
Volume 02: May 2024
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FROM THE EDITORS

Welcome to the second issue of Social Grammars of Virtuality. This is a new type of digital publication providing a high-level, critical summary of social science extended reality (XR) research. This report is intended as a resource for the global community of researchers and practitioners wishing to better understand the social fabric and communicative dynamics around XR experiences, including virtual, augmented, and mixed reality. In this issue readers can find a systematic mapping of the intellectual, geographic, and funding sources of 1,457 XR peer-reviewed, social science articles published in 2022. This is followed by sections providing a summary of cutting-edge, social science advances in XR theories, methods, technological innovations, and language.

Our deepest gratitude to Dean John L. Jackson, Jr. and our colleagues at the Annenberg School for Communication at the University of Pennsylvania for their support for this project. We also extend thanks to our colleagues and Editorial Board members who have generously shared their time and feedback on early drafts and ideas: Drs. Guobin Yang, Jessa Lingel, John Pavlik, Marcus Carter, Danny Pimentel, Donna Davis, Spencer Striker, Jasmine Erdener, and Christin Scholtz.

INTRODUCTION TO ISSUE 2

Katerina Girginova & Katie Rawson

Welcome to the second issue of the Social Grammars of Virtuality! This is a yearly report, dedicated to tracking and critically analyzing developments in extended reality (comprising augmented, mixed, and virtual reality) research. We examine a wide range of academic publications and have a vested interest in pursuing advancements in the social sciences and ways of knowing rooted in communication and media studies—areas we argue are fundamental for extended reality (XR) knowledge building, yet underrepresented in existing work.

In this issue readers will find a knowledge mapping of all of the available peer-reviewed XR publications in English in 2023 (that's a total of 8,906 papers – an ambitious number for the most avid reader, even when using ChatGPT). The knowledge mapping examines the geographies of knowledge production, key topics of inquiry, publication outlets, and funding, and provides a high-level summary of research trends. This is followed by chapters providing a deeper dive into the theories, technologies, methodologies, and language found in XR research in 2023. The report concludes with an overview of commercial innovation throughout 2023—an examination of important developments in technology that often trickle down into future academic work.

Two new developments in our report this year include the ability to compare findings with those from the previous year, 2022, and a focus on the intersections between XR and artificial intelligence (AI). Many of the chapters comparatively mention trends found in the literature in 2022, and highlight dis/continuities between the years. It is our hope that as we continue to publish these reports, yearly trends will become more pronounced and opportunities for research will become easier to identify. In addition, given the recent explosion of publicly available, generative AI tools, this issue took special interest in how and to what degree AI featured within XR research in 2023. So, each of our contributors was tasked with noting the presence—or lack thereof—of AI in their specific chapter.

KEY FINDINGS:

1. Social science publications (those examining the various social contexts and impacts of XR adoption) accounted for just over 11% of the total output of XR research in 2023 and saw the largest growth across all research disciplines from last year.

2. Augmented reality research also saw significant growth in 2023, more closely mirroring market trends globally where AR remains the most popular medium of use in 2023 with some projected 1.4 billion active mobile user devices[1] as compared to 21.8 million virtual reality headsets.[2]

3. Education, including classroom learning and specific task training, remains the most prolific area of social science research. It is also one of the top areas of research within the context of other disciplines, such as healthcare.

4. Meta is losing market share, and a plethora of new and specialized software and hardware XR tools—including those supported by AI—are rapidly emerging.

RECOMMENDATIONS FOR XR RESEARCHERS AND PRACTITIONERS:

- Theory building around XR is limited but new theories may not always be necessary. A closer look into existing work in virtual worlds or the arts—two areas with longstanding traditions of research into virtuality—may provide fruitful ground and synergies for new work.

- XR research—and now its interconnections with AI—remains a national-level priority topic with global opportunities in funding. Subsequently, those seeking funding may wish to look more broadly.

- The most prolific areas of XR research remain rooted in healthcare and computing but there is ample room for collaboration with adjacent fields, as evidenced by the presence of topics like education and training across all contexts.

The chapters in this report may be read individually, for those with a particular focus in XR work, or they may be read sequentially to give a broader overview of the research efforts underway. The report remains a free, quality resource to the academic and practitioner community interested in the field, and it is available in English and Spanish. We hope that this report presents a valuable step toward bringing communication and, broadly speaking, social science voices to the fore of XR conversations in society—and to do so in an accessible way. We view our work as a conversation with XR researchers globally. We hope that you enjoy reading it and that you get in touch to continue that conversation.

AUTHOR BIOGRAPHIES

Dr. Katerina Girginova is Co-Editor of the Social Grammars of Virtuality and Co-Founder/Director of the Annenberg Extended Reality (AER) Lab at the University of Pennsylvania. She writes about the logics of how global media, audiences, bodies, and events migrate into various virtual realms. Prior to joining the University of Pennsylvania, Katerina worked in a number of media organizations and enjoys combining creative and critical perspectives in media production.

Dr. Katie Rawson is Senior Director of Library Services and Operations and Co-Director of Media and Information Technology at the University of Pennsylvania's Annenberg School for Communication. She's held positions in digital scholarship, learning innovation, and publishing. She has published on data curation, academic collaboration, computational methods, and food culture. Whether studying data models or short-order cooks, her research focuses on ways of knowing.

Dr. Maxwell Foxman is an Assistant Professor of Media Studies and Game Studies at the University of Oregon's School of Journalism and Communication. His research focuses on how games and play impact non-game media and affiliated industries, including journalism, e-sports, and XR. Foxman is the co-author of Mainstreaming and Game Journalism (MIT Press) with David B. Nieborg. His research has appeared in New Media & Society, Social Media + Society, and Digital Journalism, among other outlets.

Dr. Jeffrey Vadala is a researcher in the field of neuroaesthetics and anthropology, focusing on how architecture shapes human experience and cognition. Through the use of virtual reality (VR), augmented reality (AR), mixed reality (MR), and artificial intelligence (AI), he studies how humans create and experience space and place. As the director of the Penn Neurology VR Laboratory, Dr. Vadala teaches and leads projects that integrate VR, AR, and AI to study how humans perceive and respond to different architectural environments.

Kyle Cassidy is Co-Founder/Director of the Annenberg Extended Reality (AER) Lab at the University of Pennsylvania and has been writing about technology since the early 1990's. He has authored a number of books about computer science and has been a contributing editor to Videomaker Magazine for two decades. He's won four Keystone Journalism Awards and in 2020 he won the University of Pennsylvania's Model of Excellence award for his work in virtual reality.

Dr. Waseq Rahman is an Assistant Professor in the Department of Computer Science, Design and Journalism at Creighton University. He is primarily interested in media entertainment. His research focuses on the use of games and gaming spectatorship in strategic communication contexts from a media psychological perspective.

Shane Burrellis a PhD student in Game Studies at the School of Journalism and Communication, University of Oregon. Shane's research is on the relationship users of virtual reality have with their virtual characters. Shane investigates this through the critical and post-positivist lens, using mixed methods and grounded approaches. Shane's research focuses on the uses of innovative technologies and media while examining this through the media psychology paradigm.

NOTE

Special thanks to all of our reviewers for their time and thoughts on this issue.

1. Figure from Statista Reports: https://www.statista.com/statistics/1098630/global-mobile-augmented-reality-ar-users/

2. Figure from Statista Reports: https://www-statista-com.proxy.library.upenn.edu/forecasts/1331896/vr-headset-sales-volume-worldwide

KNOWLEDGE MAPPING REVIEW

Editors' Note: This essay was amended in January 2025 due an oversight in the initial query criteria. The use of the term "AR" falsely included material from the biomedical sciences that were not about extended reality. See the revised, corrected query in footnote 4.

Knowledge mapping, also known as science mapping, is a process that allows us to visualize and analyze the core features of publications on a specific topic (Chen, 2017[1]). This process reveals a number of important factors about a body of literature, including its intellectual and geographical structure. Knowledge mapping also allows us to ask and answer questions like, who are the key authors within the field of social science[2] XR research? Or where is our knowledge geographically emanating from? Or who is funding this work and how democratized is the knowledge (i.e., what is its open access status)? Examined over time, knowledge mapping may also reveal paradigm shifts within a research field.

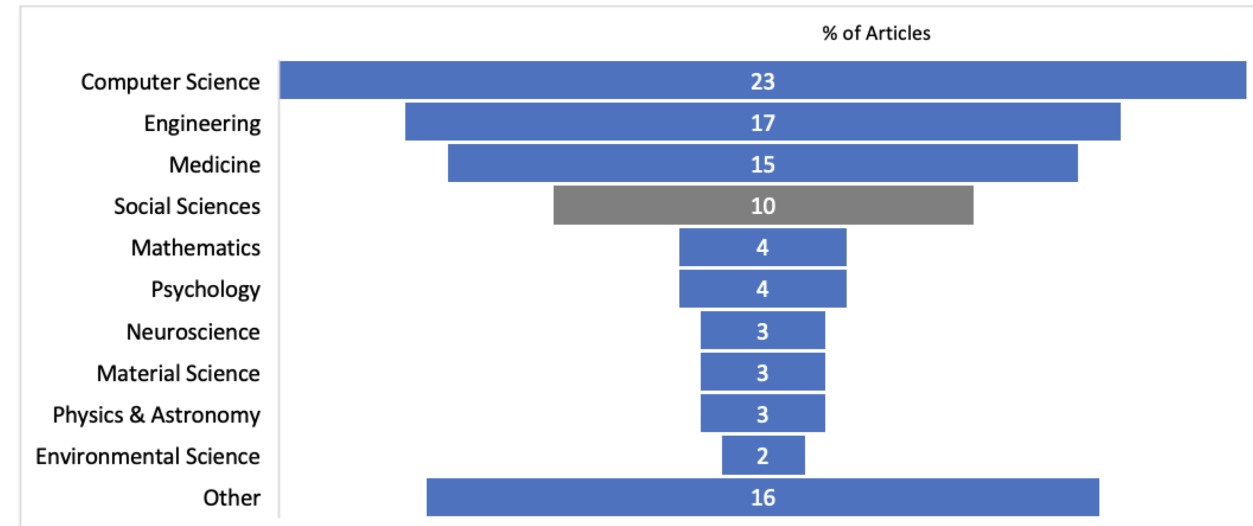
Whereas the sections on XR theory, methodology, language, and technologies that follow draw from 344 peer-reviewed articles published within three specific journals dedicated to XR research[3], this section takes a more expansive approach. In order to map out all of the peer-reviewed, social science publications in English during 2022 and to compare them to XR research efforts across disciplines, this section draws from two wider bodies of work:

- 1,457 articles, which make up all of the accessible, peer-reviewed social science publications in English during 2022.
- 8,219 articles, which include the 1,457 articles from social science publications, and all accessible, peer-reviewed articles from other disciplines that have published research in English related to XR in 2022. (Note that some articles are classified under multiple discipline categories.)

For more details[4] about the selection criteria and specific methodology applied for this review please refer to the appendix. The findings from the knowledge mapping review first situate social science XR research contextually and historically, and then delve into questions of authorship, affiliation, and funding.

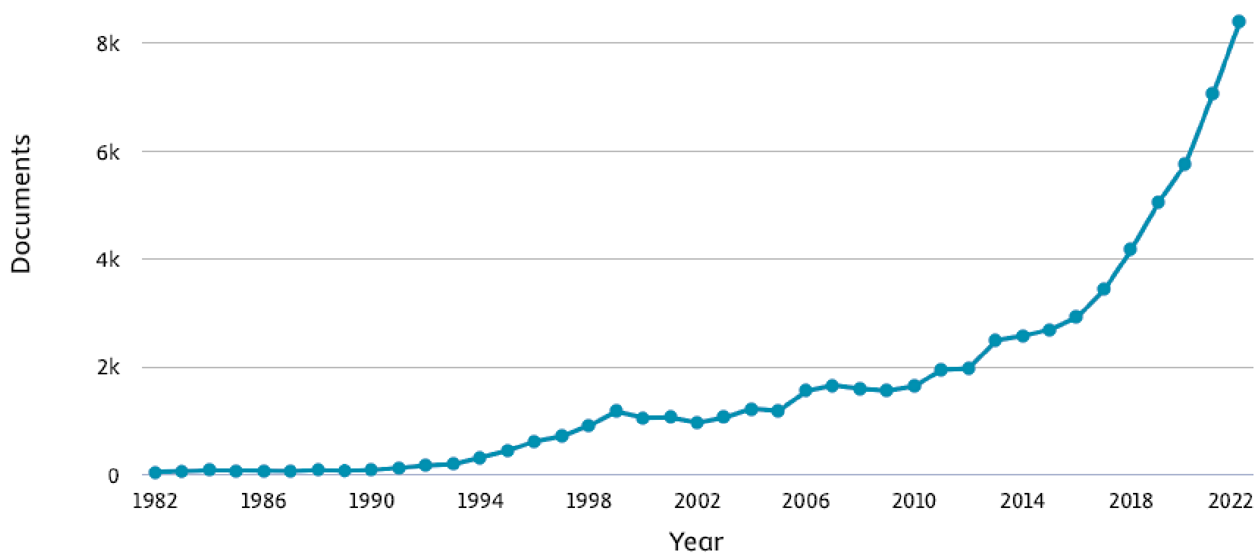
Figure 1 below shows that social sciences made up a relatively small percent (~10%) of the overall pool of 8,219 XR-related articles in 2022. As might be expected, computer science was the output leader followed by engineering and medicine, which together accounted for about 55% of the total publication output. There are several reasons for this dominance, including

Figure 1: 8,219 XR Research Documents Published in 2022 by Discipline



Nonetheless, there has been an increase in interest in XR in the social sciences, as evidenced by the upsurge in publications within the last decade (See Figure 2). This momentum coincides with what is often called the second wave of XR; that is, the phase during which XR tools became commercially available due to technological advances and lowered costs. Nonetheless, it is worth noting that the majority of the articles in both, the social sciences set, and the overall 2022 XR publication set, set were specifically about VR experiences and technologies.

Figure 1: 8,219 XR Research Documents Published in 2022 by Discipline

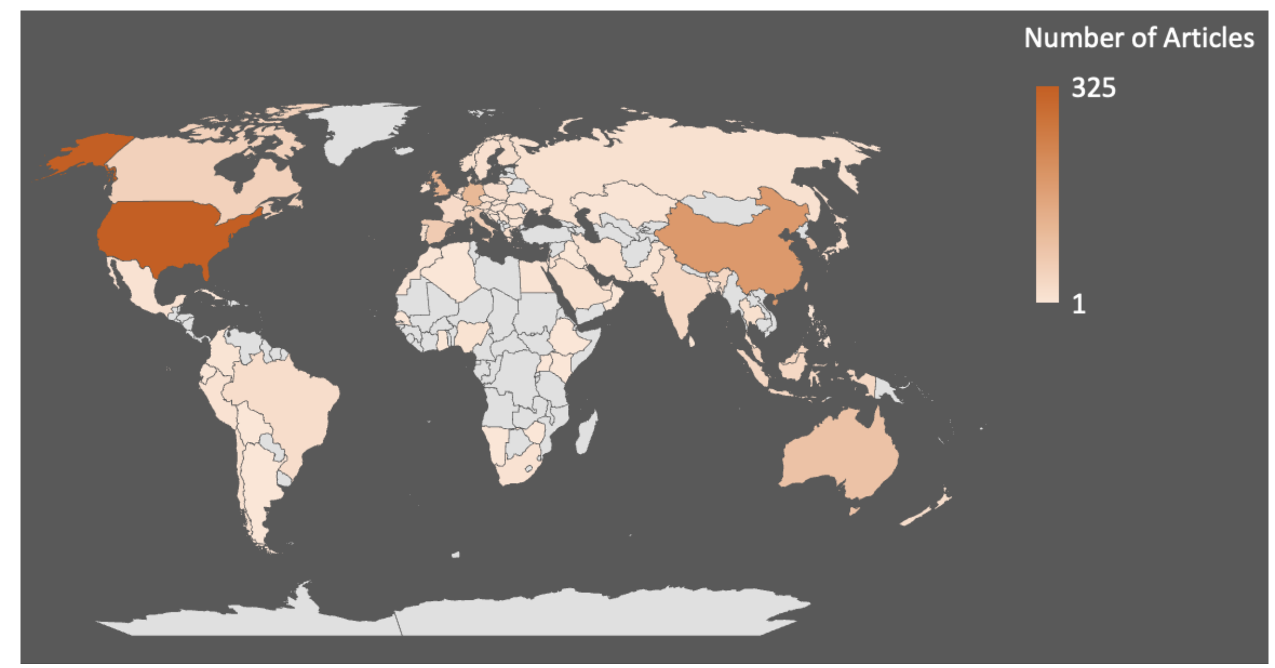


Notably, a high percent of the 1,457 social sciences articles published in 2022 were from the field of education. Furthermore, four out of the five most prolific authors (Huang, H., Mantri, A., Cheng K-H., and Makransky, G., in order of number of articles published) in the social sciences were writing about education-related topics. Upon closer review, many of these articles were inspired by the recent educational upheavals caused by the COVID-19 pandemic and examine facets of distance learning in an often-implicit precaution to similar events in the future. In fact, many of the educational or professional training advances in XR research are framed as much within the hype of democratized online learning as they are in preparation for further global doomsday mitigation.

GEOGRAPHIES OF KNOWLEDGE PRODUCTION

Out of the 8,219 XR articles published in 2022, China was the leading intellectual source (22%), with the US in close second place (20%). Within the scope of social sciences XR articles these two positions were reversed, but the output gap was significantly bigger: China accounted for 13% whereas the US for 22% of publications. Figure 3 below shows the most social science research-prolific countries globally.

Figure 3: Social Science XR Publications in 2022 by Country



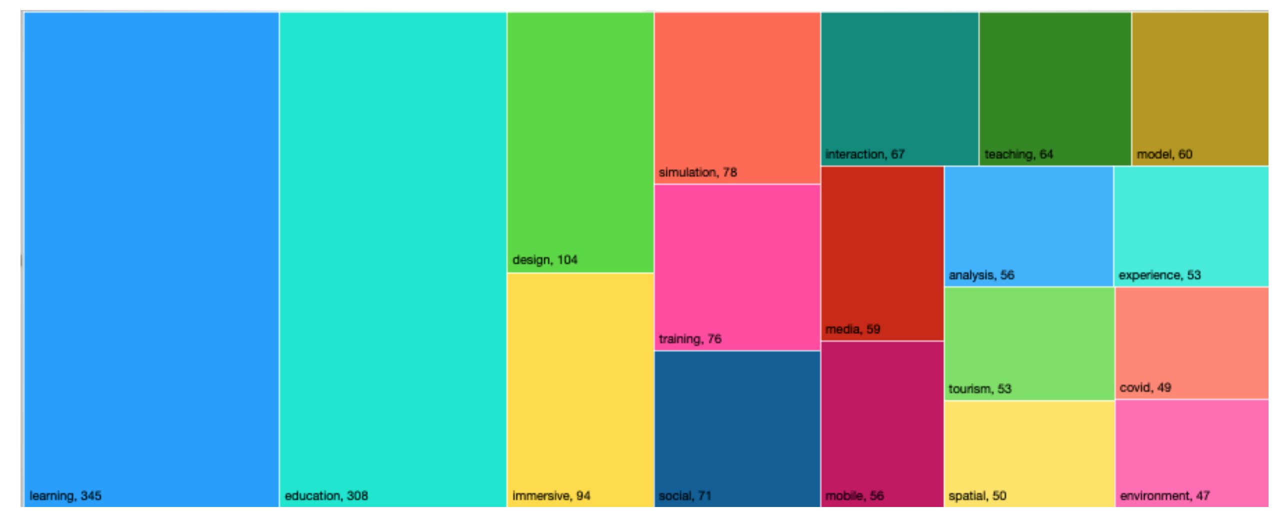
AUTHORS AND AFFILIATIONS

Over 90% of all social science XR articles were co-authored. Further, the most prolific institutions in terms of XR social science output all house multiple XR labs or departments conducting related research. The most prolific institutions were: National Taiwan Normal University, University of Florida, University of Toronto, University of Singapore, Monash University, and National Taiwan University of Science and Technology. This is a promising indication of institutional support for an emergent, global field of research. It is also a reminder of the cross-disciplinary nature of XR research, and the knowledge-production benefits of academic institutions with multiple XR labs or experts from different disciplines. Notably, as the findings suggest, it is still possible for smaller institutions and individual XR researchers to attain similar synergies through external collaborations.

On a broader scale, from the total 8,219 publications across all disciplines in 2022, the top 10 academic affiliations in XR knowledge production were all based in France, China, UK, Canada and Australia. The most prolific affiliation of output is CNRS (Centre National de la Recherche Sceintifique), which is a French state research organization and the largest fundamental science agency in Europe, with a production of just over 1% of all publications. While no single organizational affiliation dominates the research output – the most prolific one accounts for just over 1% of works – the top three organizations are all national-level bodies, which demonstrates the present importance of XR technologies. For comparison, every one of the top ten social-science publishing institutions was university. Similarly, no single institution dominated the social sciences research in 2022, with the top institution, National Taiwan Normal University, accounting for just 1% of the overall publications.

KEYWORDS

Figure 4: Top 20 Keywords from XR social science articles in 2022



The keywords reveal that the overarching themes of education and learning dominated the XR social science agenda in 2022. In addition, the environment, spatial interactions and tourism drove the research agenda, while COVID-19 remained a topic of concern.

SOURCES

Figure 5 below shows the ten most actively publishing journals for XR social science research in 2022. In addition, the three core journals dedicated to XR research, which are the main subject of analysis of the remainder of the sections of this publication, are listed at the top of Figure 5 in blue.

Figure 5: Articles per Journal

Journal Name	Number of Articles
Virtual Reality	211
Frontiers in Virtual Reality	111
Presence: Virtual and Augmented Reality	22
Sustainability Switzerland	93
Education and Information Technologies	39
International Journal of Emerging Technologies in Learning	30
Proceedings of the ACM On Human Computer Interaction	26
International Journal of Human Computer Studies	22
Computers and Education	21
Building and Environment	18
Computer Applications in Engineering Education	18
Education Sciences	17
BMC Medical Education	16

The leading journals by number of XR publications cluster around education, human-computer interaction, and environmental issues. Education is the leading context of social science research; however, sustainability and the environment make a notable appearance in 2022.

FUNDING AND ACCESS

Almost half (49% or 725 papers) of the articles designated as XR social science research were backed by some form of funding. The main funding bodies were national-level agencies, such as numerous Ministries of Education and the European Commission. As figure 6 shows, four of the five top funding sources were based in Asia (specifically Taiwan, China, and Korea). This suggests that XR is a national research priority field with numerous practical applications. It is also worth noting that hardware manufacturers like HTC, Meta, and Pico are mostly located within these top three countries.

Figure 6: Funding Sources of Social Science Research in 2022

Funding Agency	Number of Grants
National Natural Science Foundation of China, China	49
Ministry of Science and Technology, Taiwan	33
National Science Foundation, US	29
European Commission, European Union	28
National Research Foundation of Korea, Korea	27
Ministry of Education, Korea	26
Horizon 2020 Framework Programme, European Union	20
Fundamental Research Funds for the Central Universities, China	14
European Regional Development Fund, European Union	13
Ministry of Science and Technology of the People's Republic of China, China	13

While XR education and training-related research was common across all grant-funded work, some country-specific differences in additional priority contexts did emerge. Grant-funded research emanating from China and Taiwan focused on developing manufacturing, building, and tourism-related XR research. Work funded in the US had a mental-health focus, and grants from Taiwan favored work advancing technical developments and ways to stimulate creativity.

Half of the articles were classified as open access, which leaves room for improvement in the democratization of knowledge; specifically, if the work is designated of national-level importance.

1. Chen, C. (2017). Science mapping: a systematic review of the literature. Journal of data and information science, 2(2), 1-40. https://doi.org/10.1515/jdis-2017-0006

2. Our working definition of social science research refers to work that explores human society and social relationships. This includes fields such as sociology, psychology, and communication studies amongst others. However, it is worth noting that the exact selection criteria and algorithms the Scopus database used to determine what articles classify as social science are not made explicit and they do certainly affect the data obtained, even if in minimal ways.

3. The 344 articles represent all of the research publications in 2022 from the following three journals, which are specifically dedicated to XR studies: Frontiers in Virtual Reality and Virtual Reality and Presence: Virtual and Augmented Reality.

4. The following string query was updated and used in Scopus on January 23rd, 2025, to obtain the results:

TITLE-ABS-KEY ("XR" OR "VR" OR "mixed reality" OR "virtual reality" OR "extended reality" OR "augmented reality") AND (LIMIT-TO (PUBSTAGE , "final")) AND (LIMIT-TO (DOCTYPE , "ar")) AND (LIMIT-TO (PUBYEAR , 2022)) AND (LIMIT-TO (LANGUAGE , "English")) AND (EXCLUDE (SUBJAREA , "BIOC") OR EXCLUDE (SUBJAREA , "IMMU") OR

EXCLUDE (SUBJAREA , "PHAR") OR EXCLUDE (SUBJAREA , "CHEM"))

5. The category labeled 'Other' consisted of a range of smaller publication fields like Earth Sciences. In addition, some of these categories are not mutually exclusive but Scopus seems to have categorized the articles into disciplines based on the highest relevancy.

6. Keywords are based on the top 20 author-identified keywords across the 1,457 social science articles.

THEORIES IN XR, 2023

Maxwell Foxman, Shane Burrell, Waseq Rahman

In 2023, theories were not prominently debated in some of extended reality's (XR)'s most prolific journals. The entire editorial team of Social Grammars of Virtuality tasked all writers of the report to read and analyze all the year's articles from Frontiers in Virtual Reality (N = 91), Presence (N = 13), Virtual Creativity (N=13), and Virtual Reality (N=153).[1] We chose these journals because of their specific and longstanding focus on virtual reality. The team supplemented this body of literature with recommendations (N=12) from Convergence, New Media and Society, and similar outlets that stood out as pointed counterexamples to general trends. As authors of the theory section, we collectively analyzed the articles, inductively and qualitatively, coding them to identify common theories and how they were used in the pieces, meeting to compare our findings as is common with such research (e.g., Nowell et al., 2017). Publications in this corpus concentrated on XR's practical execution and usefulness in fields ranging from medicine, education, and fashion to the arts. Virtual Reality devoted much of its first 2023 issue to the administration of the medium in therapy and rehabilitation. Frontiers in Virtual Reality covered research topics like the state of women in the XR industry, medical simulations, and visualization. Many studies probed how immersive media might stimulate physiological reactions, such as testing haptics within STEM lessons (Johnson-Glenberg et al., 2023) or observing the sense of embodiment of secondary school students when employing Virtual Reality (VR—which tended to be the focus of articles over Augmented Reality (AR) or other mixed reality experiences—to learn public speaking (Valls-Ratés et al., 2023).

In this section, we first explain the major groups of theories found within this corpus. Mainly focused on users' physical and emotional responses to the technology, the most blatant invocation of theories surrounded cybersickness or the physical discomfort felt when donning head-mounted displays (HMDs). At the same time, other studies obliquely referenced cognitive and affective theories. Following this, we return to the prominent theories in last year's volume of Social Grammars (Foxman, 2023). Core concepts like presence, embodiment, and avatars were somewhat muted. This signals the normalization of staple XR theories whose effectiveness seems taken for granted and does not warrant explanation. We then discuss how the broader context within which XR is being used and adopted has neither led to the inclusion of critical/cultural theories, nor the development of novel concepts to interrogate XR's utility beyond direct physical impact. Finally, our annotated bibliography showcases articles from our collection that either contribute to existing theories or capitalize on them for novel work.

KEY THEMES: CYBERSICKNESS, COGNITIVE BEHAVIOR, AND EMOTION

As cybersickness continues to be an everyday problem, the most explicit speculation within the corpus we analyzed this year surrounded the condition caused by wearing an HMD and includes symptoms such as "visual fatigue, headache, pallor, sweating, dry mouth, full stomach, disorientation, dizziness, ataxia (movements coordination), nausea and tiredness" (Souchet et al., 2023, p. 19). Theories to explain the discomfort are both codified and plentiful. One article touched upon neural mismatch theory, or the idea that cybersickness "occurs because of a sustained conflict between visual and vestibular inputs" to evaluate the physical side effects of mixed reality (Kirollos & Merchant, 2023). Many cited work revolving around sensory motion theory, which predicts "VR cybersickness and its impact on the visuomotor performance using head rotations and field (in)dependence" (Maneuvrier et al., 2023). Affiliated postulates were also voiced: sensory rearrangement theory suggested a neural mismatch between current and past experiences (Jeong et al., 2023); subjective vertical conflict theory posited a "conflict between the subjective or expected vertical from previous experience and the sensed vertical from incoming sensory information" (Chung & Barnett-Cowan, 2023, p. 2037); and postural instability theory equated sickness with an inability to maintain posture (Chung & Barnett-Cowan, 2023). Other concepts included evolutionary theory/poison theory, which assumes the bodily reaction stems from adaptation to poison; dual-process theory, which points to potential fatigue that comes from looking at stereoscopic images; the transactional theory of stress; and sensorimotor contingencies theories (Souchet et al., 2023), among others. Many of the theories cited have decades-long histories, which authors would reference. For instance, Palmisano et al. (2022) provide an in-depth definition and review of cybersickness in their study testing how head orientation and lag may predict sickness. Their work references earlier analyses of VR simulation (e.g., Howarth & Costello, 1997) as well as foundational literature regarding the many dimensions surrounding sensory conflict theory as applied to motion sickness (Ca, 1931).

These examples also indicate the sheer breadth of notions attempting to explain cybersickness, underscoring the investment and vital importance in remedying the phenomenon. Queasiness due to XR remains problematic and one of the significant barriers to adoption. Souchet et al. (2023) note that cybersickness persists no matter the HMD used and, without a unifying theory, remains somewhat unpredictable and a "concern for workers using VR." Since it is also a bodily reaction that can be measured, it was surveyed via a variety of questionnaires such as the Simulator Sickness Questionnaire (e.g., Fantin et al.,

2023) or negative feelings subscale of the ITC-Sense of Presence inventory (e.g., Breves & Stein, 2023). However, the quest to fix this unresolved issue is still based on normative assumptions, particularly the ethics of promoting a technology that seems to cause these symptoms and the prospect that it can ever be "solved."

While cybersickness theories were explicitly referenced, concepts to fathom VR's effect on cognition and behavior were implied, under headers like "cognitive effects" (Carpio et al., 2023). Specific approaches like the cognitive theory of multimedia learning (Radhakrishnan et al., 2023) or the cognitive load "theory" were taken in a few cases. The latter framework states that an "increase in intrinsic and extraneous cognitive loads in parallel with a decrease in germane cognitive load may explain the lower performance in video learning as reported with other multimedia" (Chao et al., 2023, p. 645). XR was considered a mediating factor and a way to ameliorate cognitive issues in therapy for those who were disabled, had dementia, or had other afflictions like facial anxiety, PTSD, or stress from chemotherapy. Broader suppositions tended to be expounded regarding specific mechanisms of the technology: one paper investigated, for instance, how VR's heightened sense of presence might reduce anxiety and calm emotional turbulence (Buche et al., 2023); another compared three locomotion strategies for explaining intuitiveness (Ganapathi & Sorathia, 2023). Collectively, these works suggest XR could have some cognitive effect, albeit without in-depth theoretical backing.

Explanations of affective and emotional impact were equally murky. A few articles linked cognition and affect (e.g., Takac et al., 2023); tied emotions to "affective dimension theory," which sets values for measuring student interest (Y. Lin et al., 2023); or raised the "Theory of Magnitude" which proposes information in the brain is processed through systems of magnitude (e.g., Sadeghi et al., 2023). Other studies connected affective dispositions to the Technological Acceptance Model (TAM), which presents how technology is accepted based on perceptions of usefulness and ease of use (e.g., Wong et al., 2023). Overall, XR was broadly positioned as a palliative for social, emotional, and affective issues; one article in Virtual Creativity articulated the poetics of immersive virtual experience by drawing a parallel to the self-transcendence gained with a hallucinogen like ayahuasca (Miller et al., 2023). Nevertheless, there was a dearth of clarity or uniformity in recognizing the emotional and psychological ramifications of the technology. Instead, physiological measurements were calculated (e.g., Høeg et al., 2023; Sadeghi et al., 2023). A few articles evoked the Unified Theory of Acceptance and Use of Technology (UTAUT) to study cybersickness (Souchet et al., 2023; Voinescu et al., 2023), acceptance of VR in educational settings (Karaoglan-Yilmaz et al., 2023; Ustun et al., 2022) and for training in infection prevention (Désiron et al., 2023). UTAUT integrates earlier theories centered on technological acceptance, motivation, and reasoned action so that conditions, expectations regarding effort and performance, and social influence are factored into how people adopt novel technologies. However, its application, which incorporates some emotional and cognitive components, still reflects the scarcity of uniformity and the emphasis on quantification when trying to distinguish VR's affective import in these journals.

REVISITING CLASSIC XR CONCEPTS: PRESENCE, EMBODIMENT, AND AVATARS

Last year's report (Foxman, 2023) spotlighted the predominance of what might be considered "classic" concepts surrounding VR's potential—presence, or the sense of "being there" (Heeter, 1992); embodiment, or the ability to "change one's character or perspective" (Lachmair et al., 2022; see also Slater, 2017); and the use of avatars or a "graphical representation of a user in a virtual world" (J. Lin & Latoschik, 2022; see also Bailenson et al., 2004). While present across the literature, these concepts were neither deeply theorized nor dominant in discussions. For example, the aforementioned study examining physical head orientation to understand cybersickness defined presence as we did above—as "being there" (Palmisano et al., 2023). The lack of specificity implies that such concepts are assumed to be core to immersive experiences, rendering theorizing and reasoning less necessary within academic communities. Presence also manifested in scales and measurements to analyze everything from fire safety training (Ristor et al., 2023) to immersive exergaming (Høeg et al., 2023). One 20-point scale was devised and deployed to measure "How much do you feel like you are there?" (Palmisano et al., 2023, p. 1299). However, as the concept continues to be debated for lack of theoretical clarity (e.g., Latoschik & Wienrich, 2022; Murphy & Skarbez, 2022; Slater et al., 2022), such staid definitions seem to lack nuance. A few articles did make an effort at more complexity: for instance, looking at presence through phenomenology (Kelly, 2023); or delving into how demographic differences impact users' experience (Martingano et al., 2023).

Articles on avatars similarly concentrated less on theoretical development and more on functionality (e.g., Gonzalez Morin et al., 2023). Scholars presented a library of diverse avatars for public use (Do et al., 2023). Others utilized avatars to replicate conditions like auditory hallucinations for those with schizophrenia (García et al., 2023), or to combat anxiety induced by public speaking (Valls-Ratés et al., 2023). However, discussions of related theories like the Proteus Effect— the phenomenon of people conforming to their avatar in virtual worlds— were rare (e.g., Beyea et al., 2022; Sakuma et al., 2023). That was the case also with the allied concept of digital twins. This term has found particular traction for industrial, rather than theoretical work, including studies of traffic simulations (Rundel & De Amicis, 2023), XR applications (Tu et al., 2023), or, more fancifully, the natural environment (Harrington, 2023).

Sourcing these concepts for more general terminology demonstrates that rather than debating meanings, authors within the analyzed articles regularly deploy them to explain mechanisms in their research instead. Presence, embodiment, and avatars are acknowledged as inherently practical components that separate XR from other media. Some of this positioning may be based on the subject matters on which this year focused: medicine, therapy, engineering, and education, which dominated Virtual Reality's 2023 entries and require more applied and practical work rather than theoretical debate.

CONTEXTUALIZING THEORY AND FUTURE WORK

In the corpus studied for this volume, theory development served physical, social, and emotional outcomes. Most studies saw researchers putting theories to "work" by associating them with material examples and bodily functions rather than debating the broader contexts surrounding XR development and diffusion. Concepts around VR, such as presence, immersion, and embodiment, are simply normalizing when adapting the technology to other fields. This implies that XR concepts are better understood than ever. There is some evidence for this: for instance, Reaver (2023) called upon participatory planning theories when gathering input on urban planning in Oslo, Norway, over five weeks by youth participants armed with AR-enabled devices (e.g., smartphones, tablets), and were able to do so with ease. There is also clearly a deep well of knowledge from which these pragmatic studies draw. For instance, Martingano et al. (2023) provide a detailed theoretical history of presence in their study of it in terms of demographic differences.

However heartening this widespread adoption may be, such articles still need to deploy theory to understand such issues as labor, industry, or cultural impact. XR is approached more as an agnostic tool with a standard set of psychological and social theories to explain its implementation, at least in the journals selected for the analysis. Yet, treating the technology as such is troubling considering XR's proliferation, as evidenced by the many applied examples we identified. It would be advantageous for scholars to scrutinize the psychological states, cultural issues (e.g., gender, class), and social consequences (e.g., adoption, acceptance) that arise as XR insinuates itself into everyday life. Currently, most work precludes these analyses in the pursuit of implementation, which means that ideological assumptions about HMDs will likely continue to "lock-in" (Foxman, 2019, 2022) without significant debate.

Fortunately for XR scholars, there are existing theories that can complicate normative assumptions. Older studies have addressed many of these concerns, from Susan Langer's (1953) articulation of virtuality in the arts to Brenda Laurel's (1993) conceptions of immersive media through the lens of design. There is also a significant body of literature from the early 2000s on socializing in virtual worlds using platforms like Second Life (e.g., Boellstorff, 2015; , Boellstorff et al., 2012; Davis & Boellstorff, 2016). While one or two articles in our readings did reference this in terms of metaverse and marketing (e.g., Dudley et al., 2023; Ramadan, 2023)[2] such work remains absent from most studies. However, returning to this and their theoretical perspectives would add much-needed context regarding how different cultural groups (e.g., gender, disability, race, income) use these technologies . They also show that practicality can extend to other applications, including marketing, media and communications, and community formation.

Additionally, this year, some critically informed theories regarding XR's broader dissemination are emerging. For example, Whittaker (2023) tackles the ongoing problem of "onboarding" into HMDs through incorporation. However, perhaps the place where theorizing is growing most rapidly surrounds the broader social impact of the "metaverse." Since this particular iteration of XR is promoted as potentially occupying all parts of everyday life and communication, scholars are starting to theorize how it may alter a wide variety of social topics: "factual truth" and memory (Bay, 2023), public policy challenges (Mosco, 2023), and economics via Non-Fungible Tokens (NFTs) (Scheiding, 2023). This work adds to the literature that invokes political economy and cultural theory to investigate the industries disseminating XR (e.g., Chia, 2022; Egliston & Carter, 2022). Ultimately, these debates highlight the continued ample opportunities for employing rich theory beyond practical application as we get to know XR more intimately and it becomes entrenched in our society.

ANNOTATED BIBLIOGRAPHY

The following articles, selected from this year's analyzed corpus, span a wide variety of subjects, from avatars to journalism, and expand theoretical possibilities of how humans are represented in virtual environments.

Beyea, D., Ratan, R. R., Lei, Y. S., Liu, H., Hales, G. E. & Lim, C. (2022). A New Meta-Analysis of the Proteus Effect: Studies in VR Find Stronger Effect Sizes. Presence: Teleoperators and Virtual Environments, 31, 189–202. https://doi.org/10.1162/pres_a_00392

Beyea et al. (2022) review 56 quantitative studies on the Proteus Effect (mentioned above). They paid close attention to effect sizes, sample size, the method by which these articles used the Proteus Effect in their work, and the potential for p-hacking. Ultimately, the work gives future scholars recommendations on areas of the Proteus Effect that have yet to be researched, specifically, the moderating factors that initiate the Proteus Effect and the potential priming factors associated with avatar identification.

Ghosh, R., Feijóo-García, P. G., Stuart, J., Wrenn, C. & Lok, B. (2023). Evaluating face gender cues in virtual humans within and beyond the gender binary. Frontiers in Virtual Reality, 4(August), 1–10. https://doi.org/10.3389/frvir.2023.1251420

In this exploratory study, Ghosh et al. examined the impact of gender expression in the virtual workspace. Since more institutions are utilizing immersive workspaces for collaborations and meetings, the scholars looked at how gender can be perceived through the expression of virtual avatars. The findings from the authors' study indicated that while male or female avatars tended to fit users' gender expression, this was not the case with non-binary individuals. The results from this study expand on how immersive media can be used to express gender representations, thus adding a layer of nuance to the uses of immersive media in the workforce.

Lin, C. C., & Hsu, Y. C. (2023). The new ethical thinking in CGI immersive journalism. Convergence, 29(4), 1033–1053.

While somewhat field-specific, Lin and Hsu's work provides an excellent model for a theoretically complex and empirically rich approach to studying XR. The authors tackle the conceptually complicated notion of how "realness" can be represented in immersive journalism using computer-generated images (CGI). They return to historical examples of the medium and long-standing theories surrounding hyperreality and virtuality to do this. Then, to explore the ethical implications surrounding such concerns, they report the results of interviews and surveys with professionals in the UK and Taiwan to see how truth is represented in CGI stories. The result is a valuable model for understanding reality, virtuality, and practical discussions of how this can impact newsmakers.

Won, A. S., & Davis, D. Z. (2023). Your money or your data: Avatar embodiment options in the identity economy. Convergence.

Won and Davis confront an inherent paradox with the deployment of avatars: theoretically, users should have almost limitless possibilities regarding the avatar they choose to embody. However, this potential is often deeply restricted by what they describe as the "embodied identity economy," which ties possibilities to economic and platform prerogatives. To address this issue, they suggest a framework of avatar embodiment based on balancing consistency and discrepancy from physical identity and experience versus self-presence. Their work provides a valuable model for understanding the complicated relationship to avatars that may come as they find increased professional, social, and personal use.

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1. Some of the publications cited are from 2022 but meaningfully appeared in journals published this year (e.g., Presence).

2. It is worth noting that some authors would cite this work but not reference it directly and/or include it among broader reviews and meta-analyses.

THE LANGUAGE OF EXTENDED REALITY TECHNOLOGIES AND

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As research has shown, the ways in which we think and communicate about something, and the specific language we use to do so, directly shapes our experiences of it (Berger & Luckmann, 1991[1]; Searle, 1999[2]). In turn, the goal behind this section of the report is twofold: first, to better understand how we communicate about extended reality[3] (XR) media and experiences by examining the language used to describe them and second, to pursue innovations in the ways we conceptualize our interactions with XR media through the introduction of novel terms and concepts. This section draws from 266 peer-reviewed articles published in 2023 across four key journals dedicated to XR research[4] plus the addition of five relevant articles found beyond this scope. The four key journals, which all of the scholarly sections throughout this report analyze, were selected because they are dedicated to publishing XR work; the additional articles were based on the author's search.

One key finding is that in 2023 there is a very limited set of terms used and authors cited to describe XR media and experiences. Even articles that are focused on communicative aspects of XR, or are more qualitative or exploratory in nature, still adhere to the centripetal pull of psychological concepts like presence (Slater & Wilbur, 1997[5]), embodiment, and immersion (Biocca & Delaney[6], 1995; Biocca, 1997[7]) to explain XR media or to study specific phenomena using XR. This is similar to findings from the 2022 report on the language of XR that found research to be anchored around the same key terms without necessarily doing the work of interpretation or explanation. One might think this is to be expected, particularly given the objectivist epistemology that largely underpins the key journals from which the corpus of articles is drawn and yet, there is reason for change.

While a limited pool of descriptive terms is not inherently problematic, the ways in which we communicate about XR experiences should reflect the evolutions in our creation and consumption practices around XR technologies. Furthermore, as previous research has aptly pointed out, there are varied intellectual traditions and important differentiating markers even within seemingly taken-for-granted key terms like "presence" (Felton & Jackson, 2022[8]; Murphy & Skarbez, 2020[9]), which current research is rarely specific about. In short, there is a need if not for more terminology, then certainly for more clarity on what exactly we mean when we communicate about XR.

While not a dominating trend throughout the corpus of articles, three interrelated themes also emerge: 1) a focus on narrative, 2) sensory/spatial considerations, and 3) augmented reality. Specifically, the exploration of narrative extends to how the human senses and our immediate, physical surroundings become a part of the overall virtual reality (VR) experience, the co-creation of meaning between audience and performer and user and virtual artifact, the veracity of XR media narratives, and descriptions of the metaverse. Augmented reality (AR) was also the key topic of several articles, which offer readers empirical concepts to better depict our engagement with AR. The annotated bibliography below showcases each of these themes in more detail via a selection of articles.

Innovations in the language of XR include the introduction and systematic examination of "onboarding" and "offboarding" practices into XR media, the metaphor of the museum to structure how we think about the encoding and decoding of meaning in VR media, and the provocative suggestion to rename VR to "sensory immersion" or SI. Last, it's worth noting that the concept of Artificial Intelligence (AI) did feature in some of the articles but was not a prominent theme and when it was mentioned, it was often in hypothetical reference to what it could mean for future XR content creation. Similarly, spatial computing did not enter the literature in a meaningful way, highlighting the lag between academia and industry.

ANNOTATED BIBLIOGRAPHY: A SELECTION OF ARTICLES SHOWCASING THE THEMES OF NARRATIVE, SPATIALITY, THE HUMAN SENSES, AND AUGMENTED REALITY

Jang, S. Y., Park, J., Engberg, M., MacIntyre, B., & Bolter, J. D. (2023). RealityMedia: immersive technology and narrative space. Frontiers in Virtual Reality, 4. https://doi.org/10.3389/frvir.2023.1155700

This paper examines the meaning-making processes behind the consumption of non-fiction VR narratives. It designs a VR experiment, in which 20 people are shown a museum-like experience called RealityMedia, with various galleries showcasing the history of media. The authors argue that VR "is a new writing space in the long tradition of inscription" (p. 1), in which the consumption of narratives is akin to the sensemaking that takes place in a museum. Specifically, the authors posit that narrative sense-making occurs on three levels: the architecture of the space, the collection, and the individual artifacts.

This article presents an interesting companion to the book Reality Media[10] (2021), which explores the co-existence of older and newer media forms and the ways in which newer media like television remediate older media like radio. The authors highlight the added complexity of designing VR narratives, which now take place across visual, auditory, and spatial (and in some cases haptic) dimensions. They also draw attention to the tension of authorial control versus user agency in the level to which VR narratives need to be guided to appeal to different audiences. In turn, the metaphor of the museum and the three specific layers of meaning inscription and decoding emerge as tools for thinking about VR narratives.

Harley, D. (2023). Virtual narratives, physical bodies: Designing diegetic sensory experiences for virtual reality. Convergence, https://doi.org/10.1177/13548565231178915

This article uses a "research through design" approach (Gaver, 2012[11]) to examine how sensory experiences can be incorporated into diegetic[12] VR narratives, whereby the desired contribution of the paper is to use design "to produce questions rather than products" (p. x). As an illustration, the author discusses four specific projects that contextually insert various physical and sensory interactions into the VR experience, such as hand controllers that have been adapted to the shape and feel of a specific object, or sand beneath the user's bare feet. The paper prompts researchers and designers to expand beyond the more traditional visual and auditory narrative form, by considering how design elements in one's immediate surrounding, like the VR headset s/he is wearing or other, low-tech real objects, can be meaningfully incorporated into the overall XR experience. In turn, such a practical and conceptual expansion would also result in a reorientation of the producer's "design space."

Whittaker, L. (2023). Onboarding and offboarding in virtual reality: A user-centred framework for audience experience across genres and spaces. Convergence, https://doi.org/10.1177/13548565231187329

This paper, which is part of the expansive Story Futures project[13], is the first systematic consideration of onboarding and offboarding into VR experiences. The author defines onboarding and offboarding as the processes of ushering audiences into an immersive experience and backing out again. While the author notes that these practices have been extensively examined in the settings of theater and live performance, they tend to be neglected in the context of VR—to the detriment of those using it. Furthermore, the concepts of immersion and presence, key features of VR media, also tend to gloss over the processes necessary to get into and out of those states. Thus, including onboarding and offboarding as vital concepts to the work of immersion and presence requires us to expand our understandings of these latter VR keywords.

The author presents an adapted framework from the StoryFutures Audience Toolkit for inviting the "VR audiences into a contract of participation" (p.13). The framework asks those designing VR experiences to consider their responsibility to the audience and their desired effect via suitable onboarding and offboarding practices based on a consideration of platform, place, time, genre, and user. Finally, the author advocates for two shifts: 1) one which focuses attention away from technology and toward the user, and 2) one which moves beyond the "moment of immersion to the process of incorporation" (p. 17). The latter concept builds upon arguments that people are frequently aware of their physical surroundings even when experiencing absorbing VR content, thus onboarding and offboarding becomes a question of how to optimally lead audiences into these states of constant perceptual negotiation rather than into a final destination.

Kirwan, E. (2022). Performer/audience experience, performer perception and audience immersion. Virtual Creativity, 12(1). https://doi.org/10.1386/vcr_00060_1

This article examines three VR-mediated dance performances and juxtaposes the experiences of the audience and performers. The author argues that VR "enhances the performer's and audience's immersion, yet by doing so, separates performer and audience even further" (p. 55), leading to a non-event that is more akin to watching a film than experiencing the co-creation of meaning during live performance. As such, the article offers reflections on the evolution of dance, as a story medium that "immerses audiences through its unfolding narrative" (p. 52).

Bay, M. (2023). Arendt in the Metaverse: Four properties of eXtended Reality that imperil factual truth and democracy. Convergence, 29(6), 1698-1712. https://doi.org/10.1177/13548565231199957

This article argues that extended reality (XR) technologies inhibit the social creation of what Arendt (1968[14]) calls a common reality and factual truth because they are increasingly connected to large media conglomerates that favor profitable audience segmentation and content personalization. The author argues this personalization is particularly potent when presented via XR content, which has unprecedented powers to persuade. While the author acknowledges that the article makes an abstracted, and somewhat theoretical argument, the synergies between generative AI that can create photorealistic virtual reality content and the impact upon the audiences who consume it warrant attention.

The problem with high levels of content personalization in XR—similar to other media—is that there becomes "less basis for political interaction and deliberation—and hence, the co-construction of a common reality is inhibited" (p. 1705). However, unlike other media, hypertargeted personalization in XR can lead to some unique issues including false memory creation, not only on cognitive but also on motoric levels, and predictive processing problems. The latter is premised upon the fact that our present perception is based on our previous experiences, hence we may feel "XR-induced false memories even when… not using any XR technology at all" (p. 1707). The article concludes with a broader contextualization of XR within the debate around misinformation, false narratives and regulation. Provocatively, the author notes that AR-enhanced reality is typically not considered misinformation, but it is a space that needs close monitoring: "any regulator who is concerned about the democratic threat of mis-/disinformation mut recognize the challenge of individualized reality misperceptions such as those made possible by AR glasses" (p. 1708).

Boellstorff, T. (2024). Toward anthropologies of the metaverse. American Ethnologist, 51(1), 47-56. DOI: 10.1111/amet.13228

This article argues that anthropology, which has long studied socio-cultural practices in a range of non-mediated and mediated settings, can help us untangle the presently abundant misconceptions about the metaverse. Specifically, the author identifies four optional characteristics of the metaverse that are frequently and misleadingly described as necessary features: first, that VR is necessary to access the metaverse. Boellstorff gives the example of Second Life as a popular metaverse or virtual place that does not require VR. To underscore the proposed separation of the metaverse from VR, the author argues that "what makes the metaverse real is social immersion not sensory immersion" (p. 4). Further, Boellstorff suggests that since VR is primarily a sensory medium, it should more accurately be renamed "sensory immersion" while reserving the term virtual reality for broader consumption.

Second, the author dismantles interoperability between metaverses as a benefit; to the contrary, he argues that there is value in being able to separate one's identity in different online as well as offline settings. Third, the need for a large scale metaverse is debunked as there is value in various-sized communities—including smaller fringe ones and lastly, crypto currency is highlighted as yet another optional feature. The author argues that the framing of these optional characteristics as fundamental to a metaverse primarily benefits the big corporations building it, and further, that anthropology has valuable tools to help us decolonize future visions from promotional rhetoric and technological "lock-in."

This piece also tackles the notion that the metaverse "is already passé—supplanted by generative artificial intelligence like ChatGPT" (p. 1). In response, the author suggests that uninspired corporate visions have contributed to pushing the metaverse (and arguably VR has had a similar fate) into a hype cycle that inevitably involves becoming supplanted by the next big technology. Yet, the metaverse's history dates back to the 19th century telegraph and will continue to evolve as a place for virtual interaction "linked to physical world-place" (p. 7).

Alha, K., Leorke, D., Koskinen, E., & Paavilainen, J. (2023). Augmented play: An analysis of augmented reality features in location-based games. Convergence, 29(2), 342-361. https://doi.org/10.1177/13548565231156495

This article analyzes how the physical environment is incorporated within 11 augmented reality (AR) games. The authors uncover superimposition, blending, immersivity, and materiality as the key processes through which this takes place; however, they note that consistent with previous research, AR remains more of a marketing strategy or "gimmick" than a central part of the games. In brief, superimposition shows game content on top of the phone camera's view without responding directly to the surrounding environment. Blending is dependent upon the phone's camera to recognize suitable locations for game content to appear. Immersion occurs when the game shows the player content around them, making the player feel as if they are within the game, and materiality occurs when the game recognizes physical objects with the in-game camera and subsequently brings them into the game.

At present, AR's social imaginary far supersedes its actual uptake, and broader audiences are limited due to existing social practices around gameplay and high levels of technological errors with AR. Yet, the authors use their findings to also question the present definition of AR: "if we instead defined AR as the broader connection of virtual information to physical space in real-time, every location-based game could potentially be considered as 'augmented reality'" (p. 358). Furthermore, AR gaming is just one step in the broader social "shift towards 'augmented space'" (p. 344).

1. Berger, P. L., & Luckmann, T. (1991). The social construction of reality: A treatise in the sociology of knowledge (No. 10). London, UK: Penguin UK. (Originally published 1966).

2. Searle, J. R. (1995). The construction of social reality. New York, NY: Simon and Schuster.

3. While extended reality of XR as an umbrella term refers to mixed, augmented, and virtual reality technologies the articles almost exclusively focused on the latter two.

4. The four dedicated journals to XR research include Virtual Reality (153 articles), Frontiers in Virtual Reality (91 articles), Presence: Virtual and Augmented Reality (13 articles), and Virtual Creativity (13 articles). The five additional articles come from the journals Convergence and American Ethnologist.

5. Slater, M., and Wilbur, S. (1997). A Framework for Immersive Virtual Environments (FIVE): Speculations on the Role of Presence in Virtual Environments. Presence: Teleoperators & Virtual Environments 6, 603–616.

6. Biocca, F., & Delaney, B. (1995). Immersive virtual reality technology. Communication in the age of virtual reality, 15(32), 10-5555.

7. Biocca, F. (1997). The cyborg's dilemma: Progressive embodiment in virtual environments. Journal of computer-mediated communication, 3(2), JCMC324.

8. Felton, W. M., & Jackson, R. E. (2022). Presence: A review. International Journal of Human–Computer Interaction, 38(1), 1-18.

9. Murphy, D., & Skarbez, R. (2020). What Do We Mean When We Say "Presence"?. PRESENCE: Virtual and Augmented Reality, 29, 171-190.

10. Bolter, J. D., Engberg, M., & MacIntyre, B. (2021). Reality media: Augmented and virtual reality. MIT Press.

11. Gaver, W. (2012, May). What should we expect from research through design?. In Proceedings of the SIGCHI conference on human factors in computing systems (pp. 937-946).

12. Diegetic narrative often refers to the sound that occurs within the context of a story and that can be heard by its characters. In the context of this article, however, diegetic narrative refers to any sensory characteristics or interactions situated in the storyworld that the user directly experiences.

13. Bennett, J., Dalton, P., Goriunova, O., Preece, C., Whittaker, L., Verhulst, I., & Woods, A. (2021). The story of immersive users. StoryFutures Audience Insight Report.

14. Arendt, H., (1968). Between Past and Future: Eight Exercises in Political Thought. New York, NY: The Viking Press.

ADVANCES IN XR TECHNOLOGIES

Jeffrey Vadala

INTRODUCTION

This section provides an analysis of the state of extended reality (XR) technology in research. It is based upon a comprehensive review of academic literature, drawing from 266 peer-reviewed articles published in 2023 across key journals dedicated to XR research. The key journals examined across all sections of this report, including this section, include Virtual Reality (152 articles), Frontiers in Virtual Reality (91 articles), Presence: Virtual and Augmented Reality (12 articles), and Virtual Creativity (11 articles). Focusing on XR research usage trends for 2023, this section provides an inductive thematic analysis of research abstracts to identify key topics and trends, as well as a detailed compilation of the XR hardware and software tools most frequently mentioned in the literature. The goal is to provide an objective, data-driven overview of the XR landscape that can inform future research and development efforts. Thus, this section serves as a valuable resource for researchers, developers, and stakeholders looking to understand and advance the field of XR technologies.

METHODS

Thematic Analysis: To identify major themes in VR research literature, we employed an innovative approach using advanced natural language processing. Abstracts from relevant papers were compiled into a single text file and analyzed using Google Gemini 1.5, a sophisticated model with a 1 million token context. This method leverages Gemini's ability to identify patterns and extract insights from large unstructured datasets, mirroring recent studies that have successfully used Large Language Models (LLMs) to identify themes and sentiment in research literature (Miah et al., 2024).

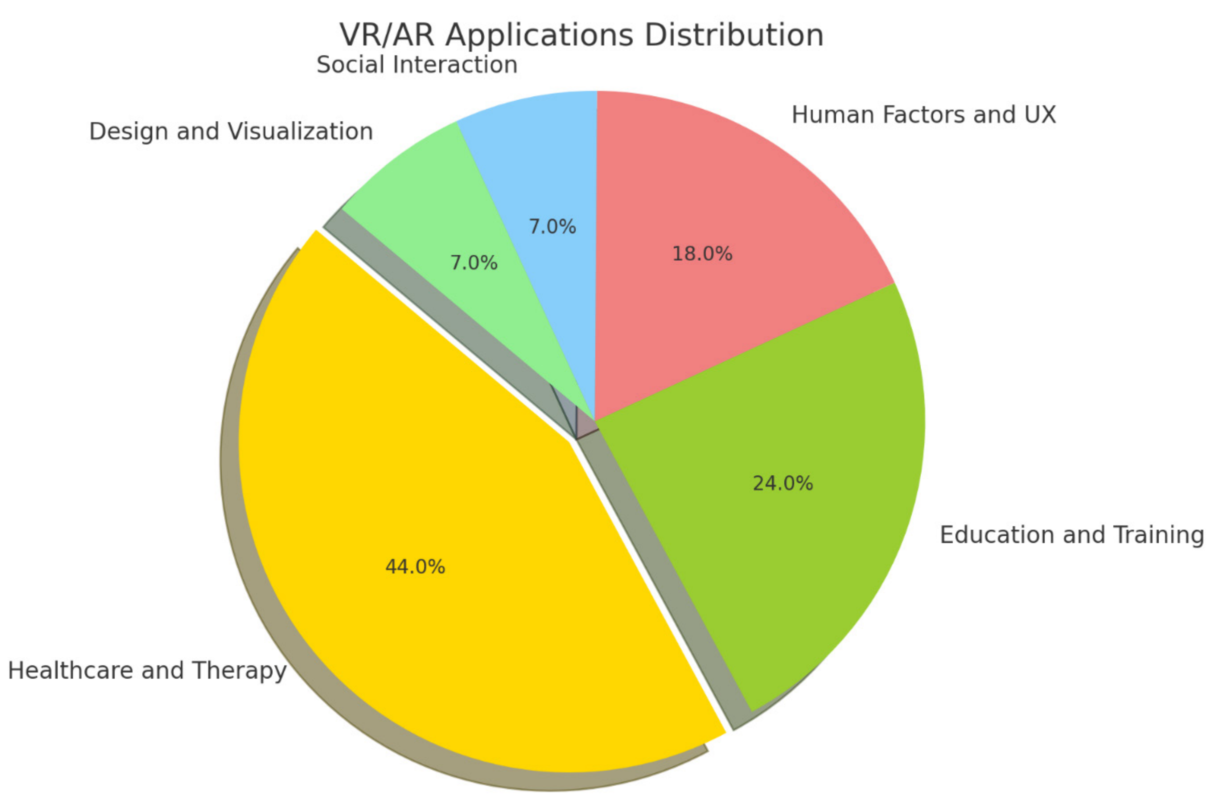
Recent research has demonstrated that LLM-based sentiment analysis approaches, which share similar methods and tools as thematic analysis approaches, can be as robust and sometimes more effective than conventional natural language tools like RoBERTA (Krugmann & Hartmann, 2024). This has led researchers to explore various ways of integrating LLMs into thematic analysis toolsets. One promising approach is the LLM-in-the-loop model, where human coders collaborate with an LLM to establish coding parameters (Dai et al., 2023). In the analysis that follows, Gemini 1.5 was used to inductively identify key themes, determine their relative prevalence as a percentage of the total literature, and provide citations and examples for each theme. This method allows for a comprehensive and nuanced understanding of the current state of VR research literature.

Hardware and Software Analysis: To compile a comprehensive list of the XR hardware and software tools most frequently mentioned in the literature, a custom Python script utilizing the OpenAI Application Programming Interface (API) was developed. This script first divided each article into 500-word "chunks" that could be processed by the API. The API was then prompted with the role of "identifying and reporting on XR hardware and software" for each text chunk. The resulting output was compiled into a structured database and summarized with OpenAI API calls to produce the final list of key VR hardware and software tools, along with frequency metrics. This automated approach allowed a much larger volume of literature to be analyzed compared to manual methods. It can be adopted for general research purposes and is provided at https://github.com/drquandary/Docparse

THEMATIC ANALYSIS RESULTS

Virtual and augmented reality (VR/AR) technologies[1] have seen rapid advancements and widespread adoption in recent years across a diverse range of domains. This report presents a comprehensive analysis of the major themes and applications of VR/AR based on a systematic review of the current academic literature. The themes identified through this inductive analysis include: VR/AR applications in healthcare and therapy (44%), VR/AR for education and training (24%), human factors and user experience in VR/AR (18%), VR/AR for social interaction and communication (7%), and VR/AR for design and visualization (7%).

Distribution of Type of VR/AR Application in Literature



Within healthcare and therapy, key application areas are rehabilitation, pain management, mental health treatment, and medical training. Education and training applications span skill training, general education and learning, and realistic simulations. Research on human factors delves into presence and immersion, cybersickness, and usability evaluation. Social interaction studies explore topics like social VR and avatar embodiment. Finally, design and visualization applications include urban planning and product design. The following sections will delve into each theme in more detail, discussing key findings, trends, and implications.

1. VR/AR Applications in Healthcare and Therapy (44%):
This dominant theme encompasses a wide range of applications aimed at improving physical and mental well-being.

- **Rehabilitation (18%):** Studies like "A haptic-feedback virtual reality system to improve the Box and Block Test (BBT) for upper extremity motor function assessment" (Dong et al., 2023), "Immersive virtual reality for upper limb rehabilitation: comparing hand and controller interaction" (Juan et al., 2023), and "A virtual reality bus ride as an ecologically valid assessment of balance: a feasibility study" (Gonçalves et al., 2023) explore VR/AR for motor rehabilitation, balance training, and cognitive rehabilitation.

- **Pain Management (12%):** Research like "Designing effective virtual reality environments for pain management in burn-injured patients" (Phelan et al., 2023) and "When virtual reality supports patients' emotional management in chemotherapy" (Buche et al., 2023) investigates the use of VR/AR to alleviate pain in burn patients and during chemotherapy.

- **Mental Health (9%):** Studies such as "Gamified virtual reality exposure therapy for adolescents with public speaking anxiety: a four-armed randomized controlled trial" (Kahlon et al., 2023) and "Co-design of avatars to embody auditory hallucinations of patients with schizophrenia" (García et al., 2023) utilize VR/AR for treating anxiety disorders, phobias, and schizophrenia.

- **Medical Training (5%):** Research like "Toward the validation of VR-HMDs for medical education: a systematic literature review" (Pedram et al., 2023) and "Utilization of virtual reality for operating room fire safety training: a randomized trial" (Katz et al., 2023) delves into the application of VR/AR for training medical professionals in surgical procedures and emergency response.

2. VR/AR for Education and Training (24%):
This theme explores the potential of VR/AR to enhance learning experiences and skill development.

- **Skill Training (8%):** Studies like "Training mental imagery skills of elite athletes in virtual reality" (Wu et al., 2023) and "Investigating the effectiveness of immersive VR skill training and its link to physiological arousal" (Radhakrishnan et al., 2023) investigate VR/AR for training complex motor skills, including sports movements and fine motor skills.

- **Education & Learning (8%):** Research such as "A phenomenological approach to virtual reality in psychiatry education" (Pedersen & Musaeus, 2023), "Embodied mixed reality with passive haptics in STEM education: randomized control study with chemistry titration" (Johnson-Glenberg et al., 2023), and "Incorporating AR/VR-assisted learning into informal science institutions: A systematic review" (Chen et al., 2023) delves into the use of VR/AR in various educational settings for subjects like physics, chemistry, and language learning.

- **Simulation & Training (8%):** Studies like "Exploring the role of virtual reality in military decision training" (Harris et al., 2023) and "Immersive virtual reality and passive haptic interfaces to improve procedural learning in a formal training course for first responders" (Calandra et al., 2023) use VR/AR to create realistic simulations for training purposes in areas like military decision-making and fire safety.

3. Human Factors and User Experience in VR/AR (18%):
This theme focuses on understanding the human response to VR/AR technologies and optimizing the user experience.

- **Presence & Immersion (7%):** Studies such as "A qualitative case study on deconstructing presence for young adults and older adults" (Pouke et al., 2022) and "Using interpretative phenomenological analysis to gain a qualitative understanding of presence in virtual reality" (Kelly, 2023) investigate the factors that influence the feeling of presence and immersion in VR/AR environments.

- **Cybersickness (6%):** Research like "Cybersickness as the virtual reality sickness questionnaire (VRSQ) measures it!?–an environment-specific revision of the VRSQ" (Josupeit, 2023) and "Predicting VR cybersickness and its impact on visuomotor performance using head rotations and field (in)dependence" (Maneuvrier et al., 2023) explores the causes and mitigation strategies for cybersickness.

- **Usability & User Evaluation (5%):** Studies like "Development of a customizable interactions questionnaire (CIQ) for evaluating interactions with objects in augmented/virtual reality" (Gao & Boehm-Davis, 2023) and "Effects of virtual reality and test environment on user experience, usability, and mental workload in the evaluation of a blood pressure monitor" (Hinricher et al., 2023) evaluate the usability and user experience of VR/AR applications and develop new evaluation methods.

4. VR/AR for Social Interaction and Communication (7%):
This theme examines the potential of VR/AR to facilitate social interaction and communication.

- **Social VR (4%):** Research such as "Understanding the effect of a virtual moderator on people's perception in remote discussion using social VR" (Yang et al., 2023) and "The sentiment of a virtual rock concert" (Slater et al., 2023) explores the use of VR for social interaction and communication.

- **Avatar Embodiment (3%):** Studies like "Immersive role-playing with avatars leads to adoption of others' personalities" (Sakuma et al., 2023) and "Evaluating face gender cues in virtual humans within and beyond the gender binary" (Ghosh et al., 2023) explore the impact of avatar embodiment on social interaction and self-perception.

5. VR/AR for Design and Visualization (7%):

This theme explores the use of VR/AR in design and visualization tasks.

- **Urban Planning & Design (4%):** Research like "Public participation in urban design with augmented reality technology based on indicator evaluation" (Wang & Lin, 2023) and "Augmented reality as a participation tool for youth in urban planning processes: Case study in Oslo, Norway" (Reaver, 2023) investigates the use of VR/AR for visualizing and evaluating urban planning concepts.

- **Product Design & Visualization (3%):** Studies such as "Digital fabrics for online shopping and fashion design" (Haghzare et al., 2023) utilize VR/AR for product design and visualization.

FUTURE RESEARCH THEMES

Although the themes here represent a broad array of topics, XR is a highly flexible set of technologies that can be utilized in a variety of research paradigms. There is ample potential for future research to make new thematic categories and to impact other fields. For example, the following topics can be found in other disciplinary journals but have yet to be substantially integrated into the research efforts of the core four journals examined in this section.

Research into the **Long-term Impact and Efficacy** of VR/AR applications will help us understand their lasting effects in areas like therapy and education. Integrating VR/AR with other technologies such as artificial intelligence and the Internet of Things could lead to smarter, more responsive learning environments and therapy sessions. Improving **Accessibility and Inclusivity** is essential to ensure that everyone, including those with disabilities, can benefit from these tools by developing adaptable interfaces. **Cross-Cultural and Ethical Considerations** are critical as VR/AR technologies reach worldwide audiences, ensuring they respect privacy, security, and diverse cultural norms. Understanding the **Economic Impact and Scalability** of VR/AR can highlight their cost-effectiveness and the challenges of broad implementation, especially in resource-scarce settings. **Integrating VR/AR with Traditional Fields** like archaeology and environmental science could open new doors for advanced environmental modeling (see Vadala and Milbrath 2016). Lastly, studying VR/AR in **Real-world and Multi-user Environments** will show us how these technologies can change the way we interact socially and operate in public spaces. By focusing research on these areas, we can enhance the reach and utility of XR, making these technologies more practical and beneficial across different sectors of society.

HARDWARE

The compilation of XR hardware and software used in studies from 2023 onward underscores a significant reliance on commercially available devices originally designed for gaming and entertainment, which are being repurposed for academic and clinical research applications. The array of hardware employed spans various brands and models, each contributing uniquely to the field of XR research.

Head-Mounted Displays (HMDs):

- **Microsoft HoloLens 2:** Highlighted in studies by Ashitiani et al. (2023) for exploring spatial understanding of brain tumors and by Kildahl-Andersen et al. (2023) for mixed reality bronchoscopy, indicating its utility in medical research.

- **Meta Quest 2:** Used in diverse contexts such as upper-limb motor function assessment by Evans et al. (2023), cognitive training for ADHD symptoms by Cunha et al. (2023), and multisensory VR nature immersion by De Jesus Junior et al. (2023), showcasing its versatility.

- **HTC Vive Pro and Varjo XR-3:** These devices are employed for detailed studies on visuomotor tracking and text legibility in VR by Baillet et al. (2023) and Kilpelainen and Hakkinen (2023), respectively, emphasizing their application in fine-motor skill analysis and visual clarity.

- **HTC Vive:** Noted for its use in investigating virtual object manipulation, glove pose estimation, and action recognition, illustrating the breadth of research from Bonfert et al. (2023) to Sakurada et al. (2023).

- **Oculus Quest and Rift S:** These units are utilized for studies on locomotion techniques, the impact of physical walking on target selection in VR, and immersive session effects on pain and affect, indicating a broad interest in user experience and therapeutic applications.

- Other Devices:

- Devices like **VR controllers, Vive Trackers, Leap Motion**, and the **Kinect sensor** are critical for enhancing interaction and movement within VR environments, supporting studies on full-body tracking and hand gesture recognition.

- **Specialized Devices** such as the VRPMST, Cybercopters, X-Board, MoVR therapy suite, PA suit, and Nesplora Aquarium demonstrate the innovative development of custom tools for specific research needs, ranging from memory assessment to haptic feedback and attention evaluation.

SOFTWARE

The software landscape in XR research is equally rich, with a focus on both commercial game engines and bespoke applications designed to extend the utility of XR beyond its initial entertainment focus.

Game Engines:

- **Unity and Unreal Engine:** Widely recognized for their role in developing immersive environments across numerous studies, these engines serve as the backbone for a vast range of VR/AR/MR applications, from educational tools to therapeutic interventions.

Other Software:

- Tools like the **Lab Streaming Layer (LSL), SPSS,** and **R** are pivotal in collecting, synchronizing, and analyzing data, ensuring that research methodologies are robust and results are reliable.

Specific VR/AR/MR Applications:

- Applications such as **Virtual_Decisions: GANGS, EnhanceVR, RealityMedia**, and the **MoVR therapy suite** illustrate the sector's move towards targeted interventions and explorations of spatial narratives, cognitive training, and therapeutic tools within the XR domain.

The analysis of VR/AR hardware and software mentioned in the literature revealed several notable trends and insights. The Microsoft HoloLens 2 emerged as the standard device in healthcare applications due to its ability to allow users to see the outside environment and its research mode functionality. However, it is important to note that Microsoft has recently abandoned the HoloLens line, making it a dead end in terms of future software and hardware development (special note – the HoloLens is still being developed for military uses).

The Oculus Quest 2 was another frequently mentioned device, which is not surprising given its increasing affordability and popularity among consumers and researchers alike. The HTC Vive, once a leader in the VR market, also appeared in many studies, despite HTC's lack of significant hardware updates in recent years. The Varjo headset stood out for its exceptionally high resolution, offering a superior visual experience compared to other devices. However, its high price point remains a barrier to widespread adoption. The recently released Apple Vision Pro is expected to match or nearly match the Varjo's resolution while being dramatically cheaper, although still costly compared to other consumer-grade headsets.

Full-body tracking using hardware-based solutions was another notable trend in the literature. Considering modern software development trends focusing on software inference and the use of small low-cost cameras, this approach will eventually be replaced by software-based inference of body tracking, leveraging advanced cameras, inverse kinematics, AI, and machine learning techniques to track and infer the users body position.

In terms of software, Unity and Unreal Engine remain the dominant platforms for VR/AR development, despite the introduction of more WebXR technologies. It is anticipated that Unreal Engine, with its superior graphics fidelity, will eventually overtake Unity for studies requiring photorealistic environments.

These findings highlight the rapid evolution and dynamic nature of the VR/AR landscape, with new hardware and software solutions constantly emerging and reshaping the field. Researchers and developers must stay attuned to these trends to make informed decisions about the tools and platforms they use in their work.

FUTURE HARDWARE/SOFTWARE ADOPTION

The current overview of XR hardware and software relies on the established headset hardware manufacturers and their corresponding software packages that have been in use for the past several years. New hardware and software approaches have emerged in 2024 that are already reshaping research. This especially in augmented reality (AR) and mixed reality (MR). This is most apparent with the use of the Apple Vision Pro which is a device that utilizes AR, MR, and VR. The Apple Vision Pro, with its combination of AR and VR, high-resolution displays, eye-tracking, and hand-gesture recognition, is now being used for neurosurgical work, surgical simulations, remote assistance and more (Cheng et al. 2024, Olexa et al., 2024). Future hardware developments promise more wireless tech, higher resolution displays, and smaller headsets. Small devices like the XReal AR glasses show promise that headsets will eventually be glasses-sized devices that will provide more flexible and seamless research uses. Technologies found in the Varjo-X4 like the super high resolution varifocal displays allow for visual focusing systems that replicate minutia of human eyesight. Releasing for PC, Sony's PSVR2 will provide an immersive haptic feedback system while several companies are releasing affordable "haptic" suits. Omnidirectional treadmills and similar technologies have also recently matured enough to provide the "holodeck" experience where users can freely move around a full VR environment using natural and embodied movement without using the commonly utilized awkward joystick teleportation and joystick-free movement schemes.

On the software side, AR is becoming more significant, with platforms like Apple's ARKit and Google's ARCore leading in object recognition and environmental mapping. Future software will likely focus on more intuitive, AI-driven interfaces that adapt to user behavior, making XR experiences smoother. Cross-platform compatibility and the integration of AR/VR with AI, IoT, and 5G will enhance these experiences even further. The opensource web standard for VR and AR and MR known WebXR has matured enough to provide near comparable rendering performance to non-web platforms while offering "no download" single click experiences (see Girginova et al., 2024). Several robust platforms like PlayCanvas and Spline offer full packages for comprehensive application development.

Finally, emerging late in 2023, the wide availability of easy to adopt Artificial Intelligence (AI) technology will soon make an impact. Machine Learning, LLMs, and visual encoder systems will soon play a role in XR research. Visual encoders like OpenAIs GPT4o which can understand complex video streams will no doubt be used in conjunction with XR recordings of user viewsheds including mixed reality or VR content. Similar yet simpler and closed functionality is already advertised for use in the Meta Quest 3 system using the Llama 3.1. This will open the doors to automatic high precision image segmentation auto coding of visual relations that previously required high amounts of Machine training and set up in component ML frameworks like YOLO. The ease and flexibility of these systems should spur new forms of systematic and automated analysis focusing on first-person user interactions while also allowing researchers to develop XR visual and audio systems that can adapt and present information and visuals based on the complex reasoning that systems like GPT4o can provide.

Neural Radiance Fields (NeRF) and Gaussian Splatting technologies are set to change graphical rendering of objects and environments for XR research. Neural Radiance Fields (NeRF) uses deep learning to generate highly realistic 3D scenes from a few images. This contrasts with traditional photogrammetry software that requires a significant time investment for photo capture, model refinement and processing. NeRF technology can capture intricate details of real-world environments, enabling more immersive and accurate virtual experiences. By reconstructing environments with remarkable precision, NeRFs are pushing the boundaries of what's possible in XR, providing more lifelike simulations for applications in gaming, training, and remote collaboration. This approach has just begun being used for a variety of disciplines including neuroscience, surgical training, forensics, and a host of simulation related disciplines (Kolpan et al., 2024).

Sometimes paired with NeRF techniques is the efficient new rendering technique Gaussian Splatting. Made possible by a variety of technological advances (efficient algorithms, GPU speed and memory increases, web xr standards), Gaussian splatting on the other hand is a technique that enhances the rendering of 3D scenes by using a collection of Gaussian functions to represent surfaces and textures. This method allows for smoother transitions and more realistic textures in 3D models, addressing some of the limitations of traditional polygon-based rendering. Gaussian Splatting's ability to produce high-quality visual outputs with less computational overhead makes it particularly valuable for XR applications, where performance and visual fidelity are crucial. More specifically, Gaussian Splatting has the benefit over traditional rendering techniques when it comes to rendering complex environments in a realistic manner without common distortions and rendering flaws associated with polygon rendering techniques which have dominated since the 1990s.

Together, NeRF and Gaussian Splatting are revolutionizing XR research by improving the realism and efficiency of 3D content creation. These technologies enable researchers and developers to create more detailed and accurate virtual environments, which can be used for a wide range of applications, from immersive training simulations to virtual tourism and beyond. As these techniques continue to evolve, they hold the promise of making XR experiences more accessible, realistic, and impactful than ever before.

CONCLUSION

This report offers a detailed analysis of the current state of extended reality (XR) technologies through a review of academic literature from core XR research journals analyzed throughout the report. Using both traditional thematic analysis and advanced machine learning, we identified key themes, trends, and insights within the XR landscape. Additionally, we compiled the most frequently mentioned hardware and software tools in recent studies.

Our thematic analysis, powered by a custom made "Doc Parser" tool that used LLM OpenAI API in conjunction with Google Gemini 1.5, identified major themes in XR research, including applications in healthcare and therapy, education and training, human factors and user experience, social interaction and communication, and design and visualization. The findings show that XR technologies significantly impact various domains, with healthcare and therapy being the most prominent. Applications in this area include rehabilitation, pain management, mental health treatment, and medical training.

The hardware and software analysis highlighted the reliance on commercially available devices repurposed for research. Notable devices include the Microsoft HoloLens 2, Meta Quest 2, HTC Vive, and Varjo XR-3, each contributing to different areas of XR research. This section also notes the introduction of new devices like the Apple Vision Pro, which integrates AR, MR, and VR, promising future advancements in resolution, wireless technology, and ergonomic design.

On the software side, platforms like Unity and Unreal Engine continue to dominate XR development, supported by specialized tools for data collection and analysis. Emerging technologies such as the Apple Vision Pro, and super lightweight AR glasses will provide new technological affordances to researchers while rendering techniques like Neural Radiance Fields (NeRF) and Gaussian splatting are set to transform 3D scene and object reconstruction and representation by providing realistic and efficient content creation methods. These advancements enable more lifelike simulations and immersive experiences, pushing the boundaries of XR.

This section also identifies future directions for research, including the need for studies on the long-term impact and efficacy of XR applications, the integration of XR with AI and IoT, and the development of more accessible and inclusive technologies. Cross-cultural and ethical considerations, economic impact, and scalability are also critical areas for future exploration. Furthermore, drawing from fields like archaeology and environmental science could even provide new research avenues in topics like spatial analysis and human perception of the environment.

In conclusion, this report provides a data-driven overview of the current VR landscape, highlighting the most active and promising areas of development. It serves as a valuable resource for researchers, developers, and stakeholders looking to understand and advance VR/AR technologies. The rapid evolution of XR requires continuous attention to emerging trends and innovations to inform future research and development efforts.

XR HARDWARE AND SOFTWARE IN STUDIES FROM 2023: A COMPREHENSIVE LIST

Based on the analysis of the provided text and responses, here's a comprehensive list of XR hardware and software mentioned in studies from 2023 or later, along with citations to the appropriate studies:

Hardware:
Head-Mounted Displays (HMDs):

- **Microsoft HoloLens 2:**
    - Ashitiani et al. (2023): Used for examining spatial understanding of brain tumors.
    - Kildahl-Andersen et al. (2023): Used for mixed reality bronchoscopy.
- **Meta Quest 2:**
    - Evans et al. (2023): Used for assessing upper-limb motor function.
    - Cunha et al. (2023): Used for cognitive training in adults with ADHD symptoms.
    - De Jesus Junior et al. (2023): Used for multisensory VR nature immersion.
- **HTC Vive Pro:**
    - Baillet et al. (2023): Used for studying the impact of task constraints on visuomotor tracking.
    - Kilpelainen & Hakkinen (2023): Used for measuring text legibility in VR.
- **Varjo XR-3:**
    - Kilpelainen & Hakkinen (2023): Used for measuring text legibility in VR.
    - Lisle et al. (2023): Used for creating and manipulating 3D paths in mixed reality.
- **HTC Vive:**
    - Bonfert et al. (2023): Used for investigating challenges of controlling rotation of virtual

objects with force-feedback gloves.
- Hsu et al. (2023): Used for studying glove pose estimation in VR.
- Li et al. (2023): Used for studying action recognition based on multimode fusion.
- Sakurada et al. (2023): Used for investigating perceptual attribution of a virtual robotic limb.
- Wenk et al. (2023): Mentioned in the context of previous studies on motor training in VR.

- **Oculus Quest:**

  - Ganapathi & Sorathia (2023): Used for studying user-elicited gesture-based locomotion techniques.
  - Lu et al. (2023): Used for investigating the effects of physical walking on target selection in VR.
  - Weser et al. (2023): Mentioned in the context of comparing navigation techniques in VR.

- **Oculus Rift S:**

  - Baker et al. (2023): Used for examining the difference between 10- and 20-minute immersive VR sessions on pain and affect.
  - Kilpelainen & Hakkinen (2023): Used for measuring text legibility in VR.
  - Palmisano et al. (2023): Used for studying differences in virtual and physical head orientation.

- **Other HMDs:**

  - **Pico G2 4K:** Used by Pedersen & Musaeus (2023) for VR scenarios in a study on emotional regulation.
  - **VR-HMDs (Virtual Reality Head-Mounted Displays):** Mentioned in various studies without specifying brand or model.

Other Devices:

- **VR controllers:** Commonly used for interaction in VR experiences across various studies.
- **Vive Trackers:** Employed for full-body tracking in studies by Berg et al. and Boban et al.
- **Leap Motion:** Utilized for hand tracking in studies by Hsu et al. (2023) and Nguyen et al. (2023)
- **Kinect sensor:** Used in some AR/MR applications, such as by Dong et al. (2023) and Bauer et al (2023).
- **Specialized Devices:**
  - **VRPMST (Virtual Reality Prospective Memory Screening Task):** Developed by Hogan et al. (2023) for assessing prospective memory.
  - **Cybercopters:** Introduced by Delcombel et al. (2023) for visualizing periodic behaviors in data.
  - X-Board: An egocentric adaptive AR assistant developed by Zhang et al (2023).
  - **MoVR therapy suite:** A suite of VR therapeutic tools created by Stamenkovic et al. (2023).
  - **PA suit:** A multimodal haptic suit developed by Kang et al. (2023)
  - **Nesplora Aquarium:** A VR-based attention assessment tool used by Voinescu et al. (2023)

Software:
Game Engines:

- **Unity:** Widely used for developing VR/AR/MR experiences across numerous studies.
- **Unreal Engine:** Also popular for creating immersive environments, mentioned by several studies.

Other Software:

- **Lab Streaming Layer (LSL):** A framework for collecting and synchronizing multimodal data in VR/AR research, highlighted by Wang et al. (2023)

  Statistical Analysis Software:

- **SPSS:** Frequently used for data analysis in various studies.
- **R:** Also employed for statistical analysis and data visualization in several studies.

  Specific VR/AR/MR Applications:

- **Virtual_Decisions:** GANGS: A VR experience for adolescent risk-taking training (Bilello et al., 2023).
- **EnhanceVR:** A multisensory cognitive training and monitoring tool (Borghetti et al., 2023; Cunha et al., 2023).
- **RealityMedia:** A testbed for exploring spatial narratives in VR (Jang et al., 2023).
- **Cybercopters Swarm:** An immersive analytics tool for visualizing data (Delcombel et al., 2023).
- **MoVR therapy suite:** Includes various VR therapeutic tools (Stamenkovic et al., 2023).
- **Nesplora Aquarium:** A VR-based attention assessment tool (Voinescu et al., 2023).
- **EPELI (Executive Performance in Everyday Living):** A VR task for assessing goal-directed behavior (Seesjärvi et al., 2023).
- **X-Board:** An egocentric adaptive AR assistant (Zhang et al., 2023).
- **VR-based fire safety module:** Used by Katz et al. (2023) for training purposes.
- **Virtual Reality Sickness Questionnaire (VRSQ):** Used for measuring cybersickness (Josupeit, 2023).
- **Presence Questionnaire (PQ):** Used for assessing presence in VR (Palmisano et al., 2023).

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1. The studies analyzed primarily focused on virtual (VR) or augmented (AR) technologies. Therefore, it is these two technologies that comprise the umbrella term extended reality (XR) in this section.

COMMERCIAL INNOVATION 2023: A YEAR IN REVIEW

Kyle Cassidy

INTRODUCTION

The findings in the various sections of this report indicate a close relationship between industry and academia. So this last section is dedicated to describing key market developments from 2023 that may shape our capacities for future knowledge production. It proceeds with a selected overview of some of the important XR industry developments in the past year, covering virtual reality (VR), augmented reality (AR), Artificial Intelligence (AI), and digital twins.

EVOLUTION OF XR HEADSET MARKET SHARE

Since Q4 of 2020, Meta has dominated the XR headset market and by Q4 of 2023 Meta remain in the lead with a 72% dominance. However, in 2023 Sony also (re)entered the market and captured a significant share; between 15-33% depending on the quarter. See Statista (2024) for a graph depicting market share distribution. It will now be interesting to track market shifts in 2024 given Apple's entry into XR headsets.

DEVELOPMENTS IN VIRTUAL REALITY AND AUGMENTED REALITY

VR hardware like headsets or head mounted displays (HMDs) have an overall larger market share than AR hardware, such as smart glasses. The primary market driving sales across both technologies remains at the industry and enterprise level (Grandview Research Report, 2023). However, VR hardware saw some decline in sales in 2023, whereas AR hardware sales largely grew (IDC Report, 2023).

In VR, Meta (aka Facebook) still dominated, but with some cracks starting to appear in the armor. Meta released their Quest 3 headset (a $500 follow-up to both the $1,500 Quest Pro and $400 Quest 2) that took features from both and essentially made them obsolete. While the Quest 3 is thinner, it is half an ounce heavier than the Quest 2 on account of a larger battery (though not longer battery life, a key limitation of all standalone HMDs)[1]. A heavier HMD may lead to comfort obstacles in the long-term use of the device, and may also limit lengthier user engagement, like watching a full-length immersive film[2]. Still, there were some interesting developments in the Quest 3 like the inclusion, for the first time, of a Time-of-Flight sensor that uses a laser to measure distances and reduces the need to create manual guardian boundaries for VR room scale use (though at the time of writing, using the automatic guardian isn't easier to set up than the manually created one).

One of the big, though largely unheralded, stories of 2023 has been a series of end-runs around Meta from indie developers. For example, an indie game modder who goes by the name of Praydog released a Meta hack called "FLAT2VR" on New Year's Eve that allows nearly any flat screen game created with the Unreal Engine 4 or 5 and available on Steam to be played in VR[3]. Previously Meta's software store lacked almost any "AAA" or top of the line experiences, but after FLAT2VR's release, suddenly as many as 11,000 new PC games became available (caveat: while 11,000 games became available, the gaming community has so far (Feb 2024) tested about 1,000 and found them to work well). In addition, Meta's big news in September of 2023 was that its avatars would finally get legs instead of just being floating torsos. This decision has been long awaited and ridiculed—by comparison, Horizon World's social VR precursor of VR Chat has had legged avatars since its 2014 release—yet, was delayed not only on account of technical difficulties but also, as suggested by many[4], as an attempt to prevent virtual harassment.

Taiwanese electronics company High Tech Computer Corporation (HTC), which had been the main competition for the Oculus since the first Vive VR headset came out in 2013, released new headsets in 2023. Their Vive XR Elite is a premium consumer XR device with a nice form factor, a rear-mounted battery and no top head strap to accommodate different hairstyles (an inclusivity problem that all versions of the Meta Quest have had). One big advantage of the XR Elite Pro is its built-in diopters, meaning almost everybody can use it without their glasses. However, the Quest's lower price, wider field of view, and higher resolution makes the XR Elite Pro a hard mass market sell.

Bigscreen, whose main product until recently has been the multi-user VR theater that allows people to watch films and videos in a realistic virtual theater, also branched out into physical hardware in 2023. Bigscreen Beyond is the world's smallest VR headset (which only connects to a PC). At the time of writing, Bigscreen Beyond is the only all-day-wearable VR headset and it is custom-fitted to an individual, making it difficult to share or use in a lab space[5].

Lastly, dedicated niche AR devices (call them "smart glasses"- you'll get fewer weird looks) took some big strides into the mainstream since their market inception in 2013 with Google Glass. A number of developers realized that the technology for projecting phone apps onto simple glasses is inexpensive and relatively unchallenging. For instance, the Vuzix Blade has a built-in camera, QR Code reader, and single-eye display, which makes it ostensibly useful for things like teleconferencing, museum use, or presentations. Several companies like XRAI, LEION and Vuzix have also debuted speech-to-text AR glasses, which subtitle the live world around you by recording and translating conversations in real time thus, creating the potential for greater inclusivity in use.[6]

ARTIFICIAL INTELLIGENCE

One of the challenges in designing large-scale VR environments, or "open worlds," is the resource intensive process of crafting all the elements in them. For example, in creating a hypothetical VR simulation of Revolutionary War era Philadelphia, designers would need to create interior floorplans for every building, contents for every kitchen drawer, and the temperament of every Tory-sympathizing bar patron among a host of other things. In the past, this was done by individual designers at great cost, thus limiting the output of content and the number of organizations and individuals that could afford to build these environments. However, combining AI with VR has the potential to significantly ease this bottleneck.

Building upon last year's developments, graphic card maker NVIDIA launched generative 3D content creation with text-to-object AI in 2023, allowing VR creators to easily create, add, and manipulate 3D objects into VR content as well as a separate AI application (called move.ai) for animating 3D objects. Mobile application newcomers Luma Labs released a similar product, Geni, for creating 3D objects for AR in 2023, and Unreal Engine released a procedural content generation framework, which uses AI to provide an enhanced toolkit for users. NVIDIA also announced that with 3D face scans they can create mesh framing for easily replicating 3D versions of people[7]. Still, this process is in its infancy and comes with a range of ethical concerns. A similar model, Google's Gemini AI, recently received wide criticism and was temporarily suspended for generating ethnically diverse Vikings and Second World War German soldiers (The Guardian, 2024).

Sample image from NVIDIA of generative AI-created 3D animals which now take seconds to create and export. Image Credit: NVIDIA Developer Blog, 2023.

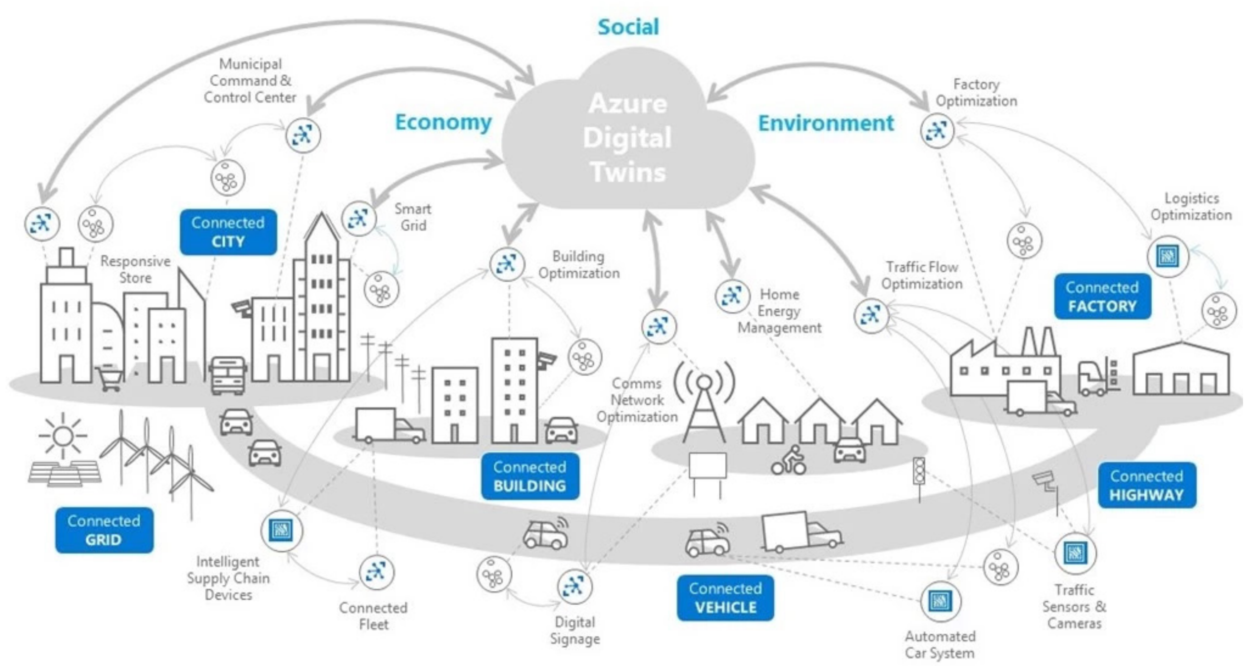
Still, the synergy between AI and VR is useful not only for world-building but for more mundane tasks like upscaling and creating spatial video out of ordinary flat video, squeezing more life out of existing retro footage and potentially expanding its applications.

DIGITAL TWINS AND VIRTUAL POSITIONING SYSTEMS

2023 saw significant developments in the technology for capturing and recreating real spaces. Niantic's "Lightship Visual Positioning System" (VPS), launched in 2023, is a Visual Positioning System which provides GPS-style coordinates for augmented reality mapping in the real world[8]. This is helpful in creating a real world metaverse, allowing for the persistent positioning of virtual objects for multi-user experiences. For instance, dozens of people can look at the same thing at the same time and objects can be shared and manipulated (think virtual art, signage, or even recreations of structures that no longer exist in a space). Lightship is primarily envisioning their VPS as a framework for games, but it would be useful for an array of virtual object that could replace a physical object, particularly in places where putting physical signs is not desirable—for example, virtual lines drawn on the ground to lead you around a historic site or place markers to show habitats of animals.

AR devices, such as smartphones, use cameras to anchor images to local environments, but in order to anchor an AR experience on Earth as opposed to, say, your living room—and for that experience to be persistent and visible to multiple users at the same time—a worldwide positioning system becomes necessary. Lightship claims to have "centimeter precision" (something GPS alone is incapable of). Lightship does this by meticulously mapping certain places they call "wayspots" and anchoring them to one another, which means that practically the system will work more efficiently in some places than others (much as Google Earth has significantly more data around large cities and densely populated places than it does rural areas). As more wayspots get created, the map gets bigger and more accurate.

While Unity stepped back in digital twin hosting, Microsoft Azure pressed ahead with Azure Digital Twins, a cloud-based Internet of Things platform that allows for the creation of digital spaces mimicking real world 3D environments—useful for helping to create a smart building or even city and to analyze data from smart sensors in and around that area to create a visual way to see. For example, you could measure how the opening and closing of blinds on various sides of a building will regulate its temperature. An entire digital twin city might use sensors to monitor traffic flows to help predict and avoid traffic congestion or to slow traffic down at times and places that are particularly dangerous to pedestrians. Yet, developments in digital twin technologies also increase the ability for and concern around surveillance. This work requires massive amounts of data collection and even more massive amounts of storage and processing power, which is a space that Microsoft Azure has carved out.



Azure Digital Twins Concept. Image Credit: Microsoft Azure Blog, 2018

Lastly, Neural Radiance Field technology (or NeRF) released smartphone software for producing real-time, full volumetric, photorealistic NeRF rendering on the web, which can use images captured not just from latest model iPhone, but even brief drone video flybys. This allows for areas and objects to be very quickly captured from a variety of viewpoints and it uses AI to fill in missing spaces – a boon to anyone studying 3D objects, places or environments.

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IDC Report, 2023: https://www.idc.com/getdoc.jsp?containerId=prUS51574023

1. See: https://arvrtips.com/meta-quest-3-vs-pro-vs-2-vs-1/
2. The capacity for full-length film was one of the main factors in the success of VHS over the technically superior Beta video format.
3. See: https://arvrtips.com/uevr-praydog-flat2vr-mod/
4. See: https://www.bbc.com/news/technology-60247542
5. See: https://www.engadget.com/bigscreen-beyond-review-gunning-for-vr-throne-valve-index-190004793.html
6. See: https://www.hearingtracker.com/resources/hear-with-your-eyes-five-ar-live-captioning-glasses
7. More about some of NVIDA's 3D content generation here: https://blogs.nvidia.com/blog/omniverse-accelerates-game-dev/
8. More on Lightship here: https://lightship.dev/products/vps/