SOCIAL GRAMMARS OF VIRTUALITY 2026

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

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FROM THE EDITORS

Welcome to the fourth issue of the Social Grammars of Virtuality! This report is dedicated to providing a high-level, critical summary of extended reality (XR) research, with a focus on the social sciences. The Social Grammars is a valuable resource for the global community of researchers and practitioners wishing to better understand developments in XR experiences, including virtual, augmented, and mixed reality. The report is available, free of charge, in English and in Spanish.

In this issue readers can find a mapping of the intellectual, geographic, and funding sources of XR peer-reviewed articles published in 2025. This is followed by sections providing a summary of cutting-edge advances in XR theories, technological innovations, and the language of XR scholarship. There is also a section dedicated to key XR market developments in 2025 and, new for this issue, a special section that examines XR dissertations.

We hope you enjoy reading the report and that you get in touch.

Katerina & Katie

EXECUTIVE SUMMARY: 2025 IN REVIEW

Katerina Girginova, Katie Rawson, Maxwell Foxman, Shane Burrell, Shravan Regret Iyer, Youngjun Lee, Sanghoon Kim, and Kyle Cassidy

Welcome to the fourth issue of the Social Grammars of Virtuality—the first and only annual report dedicated to tracking trends in extended reality (XR) research. In this issue we present the trends shaping our knowledge about XR through a birds-eye-view analysis of all the peer-reviewed articles published in 2025 in English (that's over 11,000 articles!). We continue our deeper dive into the theories, methods, technologies, and language used in XR research across three core journals[1] through dedicated sections in the report. This year, we are also pleased to present a special section that examines how wearables are shaping the future of immersive technologies.

Our analyses show that in 2025, XR research is maturing, becoming more discipline-specific, and remains largely driven by industry connections.

KEY TAKEAWAYS INCLUDE:

- The most common word used to describe XR experiences and technologies across all disciplines is 'immersive'.
- Core XR theories—presence, immersion, embodiment, cognitive load, cybersickness—are so entrenched that authors often use them without definition. Growth areas like medicine, HCI, spectatorship, haptics, and game design apply these classic theories in new contexts rather than replacing them.
- XR research methods primarily center on empirical investigation, including experimental and quasi-experimental approaches to test the effectiveness of XR technologies. This leaves plenty of room for more qualitative and ethics-centered research.
- Immersive technologies are becoming body-aware. Sensors that track muscle signals,

1 The journals we examine in the theories, methods, technologies, and language sections of this report are: Frontiers in Virtual Reality, PRESENCE: Virtual and Augmented Reality, and Virtual Reality. We cover over 300 articles.

eye movements, heart rate, and skin conductance are increasingly built into XR devices, turning headsets and smart glasses into platforms that can detect and respond to what is happening inside the user's body in real time.

We hope the Social Grammars will continue to serve as a valuable resource for the global community of researchers and practitioners wishing to better understand developments in XR experiences. As always, the report is available, free of charge, in English and in Spanish. Enjoy reading this report and feel free to get in touch.

The Social Grammars of Virtuality Team

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 global media and audiences with a specific interesti in the immersive media industry. 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 Co-Editor of the Social Grammars of Virtuality and Director of the Library and Co-Director of Media and IT at the University of Pennsylvania's Annenberg School for Communication. She has published on data curation, archives, 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.

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. Sanghoon Kim is an assistant professor in the Department of Kinesiology at Michigan State University. He teaches sport management courses within the Applied Sport Science program. His research focuses on sport consumers' experiences in emerging technology-mediated environments, including social media, mobile and self-service technologies, and augmented and virtual reality. Drawing on cognitive, social, experiential, and data-driven perspectives, his work explores how digital sport experiences shape consumer engagement, well-being, decision-making, and behavioral responses.

Dr. Youngjun Lee is a postdoctoral research fellow in the Department of Pediatrics at Children's Hospital of Philadelphia (CHOP) and an affiliated postdoctoral researcher with the Annenberg Extended Reality Lab at the University of Pennsylvania. He received his Ph.D. in Kinesiology from Michigan State University, where his dissertation examined the effects of immersive virtual reality exercise on depressive symptoms in young adults with autism spectrum disorder. His research focuses on the intersection of immersive technologies, physical activity, and mental health in individuals with neurodevelopmental disabilities. Drawing on digital health informatics, wearable biosensing, and technology-based intervention design, his work explores how XR-mediated experiences can support physical and psychological well-being across diverse populations.

Dr. Shane Burrell Jr. has a PhD student in Game Studies from 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 and he focuses on the uses of innovative technologies and media while examining this through the media psychology paradigm. Shane is currently a postdoctoral researcher with the Chestnut Health Systems.

Shravan Regret Iyer's research explores the uses of and engagement with extended reality (XR), including augmented reality (AR) and virtual reality (VR). More specifically, his work examines two intertwined strands of scholarly inquiry: the intricate relationship between society and media technology, and the evolving landscape of science and health communication amid contemporary information challenges. He holds a Ph.D. in Communication, Information, and Media and currently works as a Lecturer in the Department of Journalism and Media Studies at Rutgers, The State University of New Jersey..

XR KNOWLEDGE MAPPING 2025

Katerina Girginova

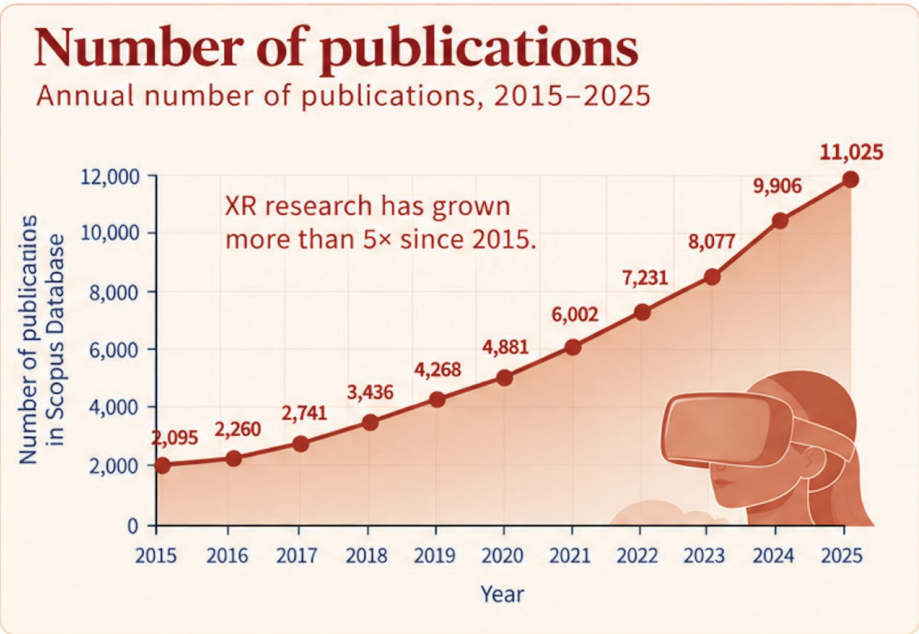
This section of the report provides a birds-eye-view of all XR research published in peer-reviewed journals in English in 2025. In total, this covers over 11,000 articles. The articles are analyzed to reveal research trends and geographies of knowledge production, as well as funding and open access information. In addition, special attention was paid to developments in XR social science research. This is because the Social Grammars of Virtuality team believes that a humanistic and critical approach to XR technologies is highly valuable yet often absent. More details about the methodology used to obtain results can be found at the end of this section.

HIGHLIGHTS

- There were 11,025 XR-focused, peer-reviewed publications in 2025.
- The volume of XR research papers[1] continues to see a steady increase over the past 10 years (2015-2025).
- Research is often practical or experimental and centered around specific technologies.
- Virtual reality continues to dominate the research field despite more people experiencing augmented reality technologies on a daily basis.
- For the first time, terms like AI, deep learning, and machine learning dominate across author designated keywords. This suggests a rapid convergence between XR and AI is underway in research.
- Social science was the fastest growing XR subject area in 2025, though it did not account for the most publications

1 Data was obtained through Scopus database using the following search query: TITLE-ABS-KEY ("virtual reality" OR "extended reality" OR "augmented reality" OR "mixed reality") AND (LIMIT-TO (PUBSTAGE , "final")) AND (LIMIT-TO (DOCTYPE , "ar")) AND (EXCLUDE (SUBJAREA , "BIOC") OR EXCLUDE (SUBJAREA , "IMMU") OR EXCLUDE (SUBJAREA , "PHAR") OR EXCLUDE (SUBJAREA , "CHEM")) AND (LIMIT-TO (PUBYEAR , 2025)) AND (LIMIT-TO (LANGUAGE , "English")) AND (LIMIT-TO (SRCTYPE , "j"))

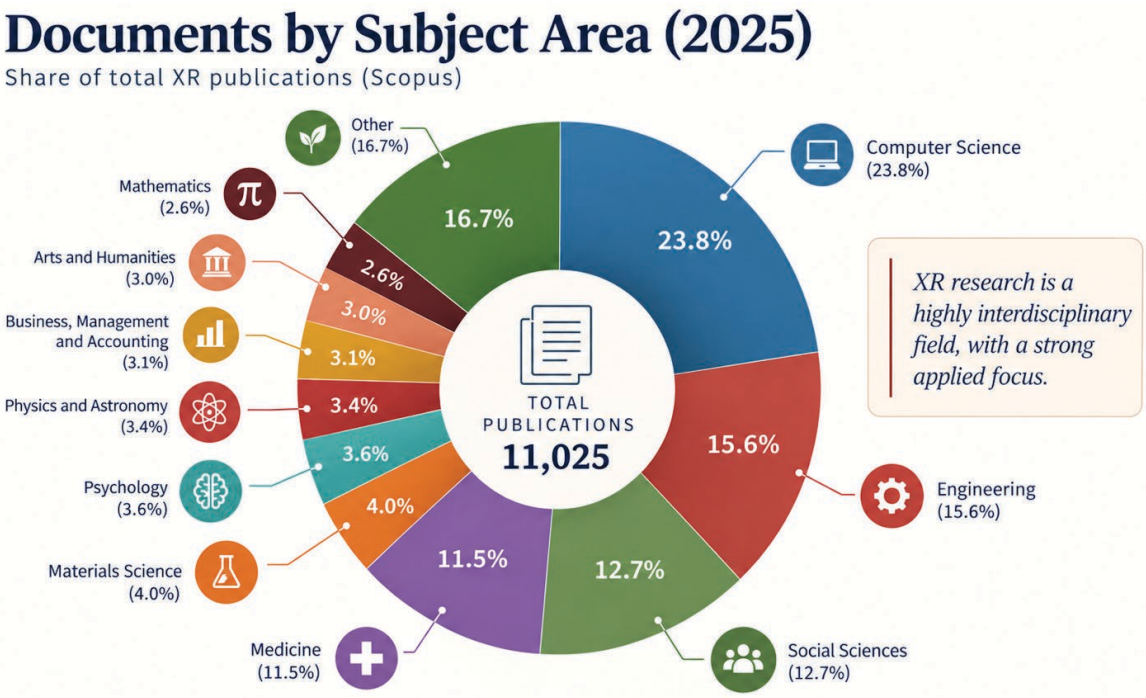
For more information see Notes on Methodology at the end of this section.



XR RESEARCH BY SUBJECT AREA

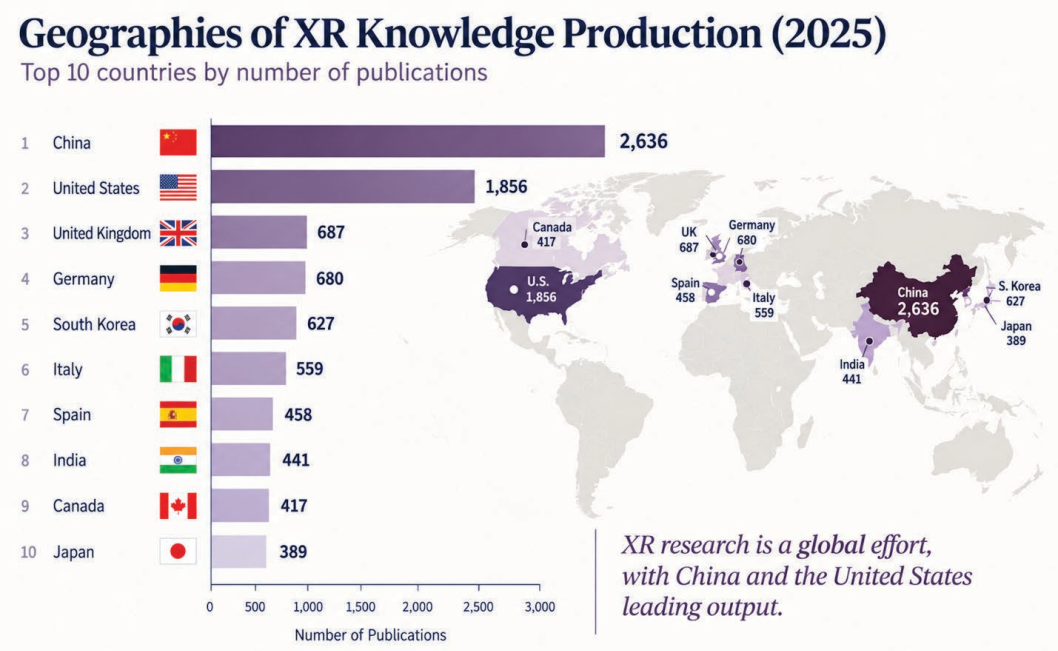
- Applied fields with a strong connection to technological development continue to prevail among the publications.
- Yet, social science[2] publications are the fastest growing XR subject area.
- Computer science, which leads subject area publications, saw a small decrease in output from last year. So did engineering (ranked 2nd by paper output) and medicine (ranked 4th by paper output).

2 This report uses Scopus definition of 'social sciences' for analysis. According to Scopus, there is a broader definition of 'social science' that includes Health Sciences, Life Sciences, Physical Sciences, and Social Sciences & Humanities. There is also a narrower list that includes 23 specific areas comprising the social sciences. See Notes on Methodology for a snapshot of these 23 specific areas.



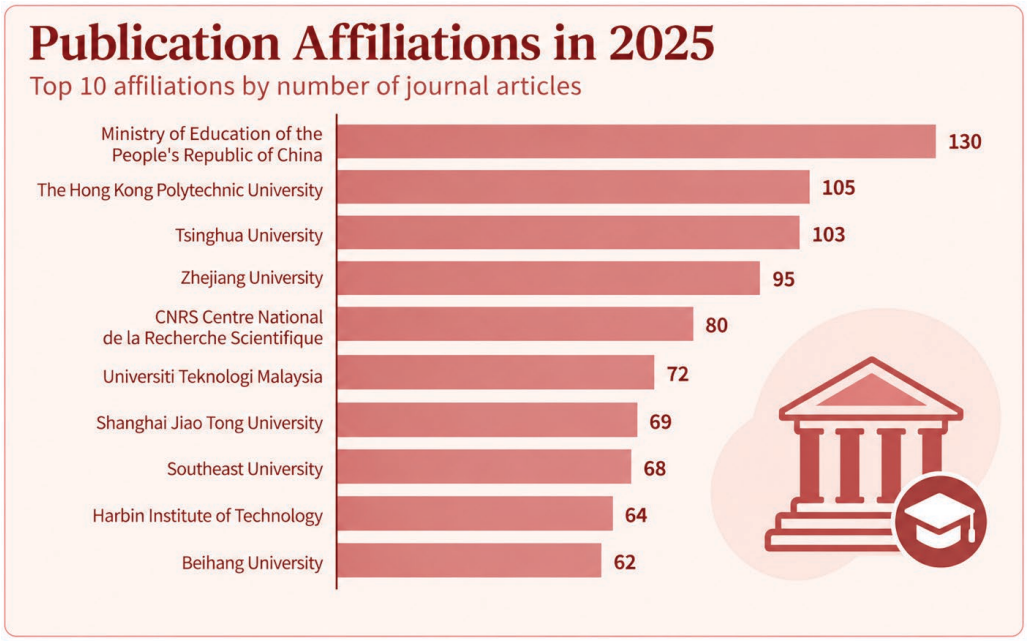
WHAT ARE THE GEOGRAPHIES OF XR KNOWLEDGE PRODUCTION?

- Since 2022 China has produced the largest volume of English language XR publications. The US comes in 2nd place per publication output.
- Within the social sciences, which is the fastest growing subject area, the geographies of knowledge production are reversed. The US accounts for the greatest volume of publications and China comes in second place.
- This year, within the US, Florida emerges as a leading cluster of knowledge production. This can be attributed to the State's synergy of research-focused universities, the entertainment industry, and aerospace, marine, and defense organizations.
- Still, no institution dominates the XR research field. Even the most active institutions per publication output in 2025 only account for just under 2% of the total publication count.



XR PUBLICATIONS: AUTHORSHIP AND AFFILIATION

- Collaboration is structural.
- Large teams dominate, with about half of all publications having 5 or more authors.
- Conversely, only 6% of all peer-reviewed XR publications in 2025 have a single author.

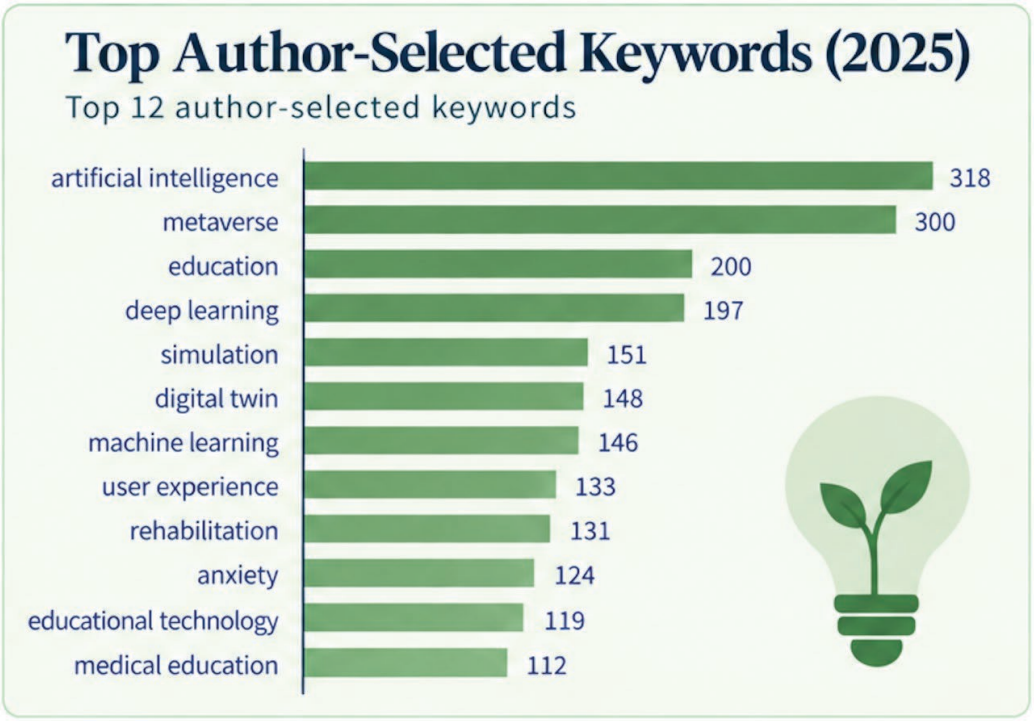


WHAT IS XR RESEARCH ABOUT?

This analysis is based on author keywords, which diverge from indexed keywords in being more descriptive. In addition, the terms virtual reality, augmented reality, mixed reality, extended reality, and VR and AR have been removed.

- For the first time in the history of XR research, AI has become the top author-indexed keyword. In addition, terms like 'deep learning' and 'machine learning' make notable debuts.
- The term 'metaverse' has also peaked in academic research, highlighting both a lag between industry and academic discourse, and the close link between XR research and industry.
- Applied contexts and training and learning use-cases make a strong appearance with terms like education, simulation, rehabilitation, anxiety, educational technology and medical technology.
- Digital twins make a notable appearance in XR research for the first time.
- Lastly, only 6% (or 640 articles) mention any theory in their keywords or abstract. Among

those that did, presence, and variations of the Technology Acceptance Model (TAM) appear most frequently.



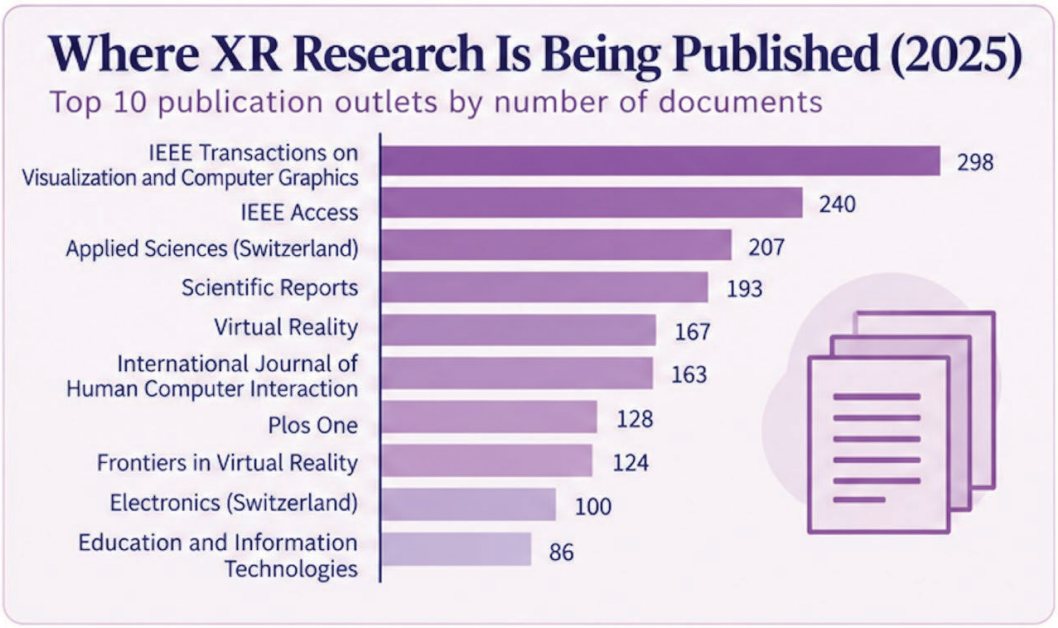
WHAT TECHNOLOGIES ARE BEING RESEARCHED?

- Of the 11,025 articles obtained, around 7,000 (or about 64%) are indexed solely under 'virtual reality'; 2,000 (or 18%) are indexed solely under 'augmented reality'; 650 (or about 6%) are indexed under solely 'mixed reality'; and less than 600 (or 5%) are indexed under 'extended reality' alone.
- Combining XR technologies within the same research project is rare.

WHERE IS XR RESEARCH PUBLISHED?

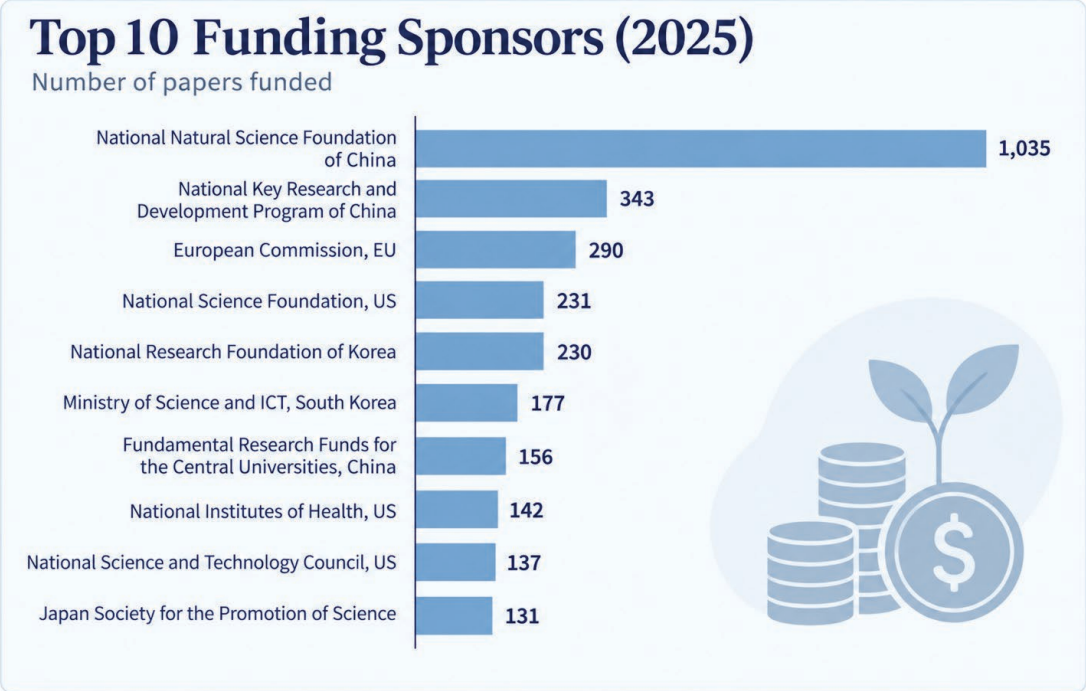
- In 2025 the top publication outlets once again show a heavy focus on technical, applied

research.



HOW IS XR RESEARCH FUNDED, AND WHAT TYPE OF WORK IS BEING FUNDED?

- The largest share of funded XR papers coalese around the topic of technology development (~4,000 papers), with education being the largest applied domain (~2,000 papers), followed by healthcare (~1,000 papers). The combination of XR and AI is also making a significant inroads this year (~500 papers).
- The top funders for the social sciences are similar to those across all disciplines.



- Some of the top funders of XR social science publications globally include the National Natural Science Foundation of China (China), the National Science Foundation (US), and the European Commission (EU).
- Each of the top funding bodies supports a wide range of work. However, certain area-specific patterns of funding also emerge:
    - The NSF has funded work around enterprise XR adoption, education and training, and gender.
    - The National Natural Science Foundation of China has funded research on education and training, as well as tourism, culture, and urban management.
    - The European Commission has funded projects on sustainability and the environment, and the ethics and safety of XR data practices.

HOW ACCESSIBLE IS XR RESEARCH?

- On average, just over 60% of all XR papers in 2025 are open access. The open access publishing designation allows a wider range of readers to access paper findings free of

charge. This is similar to last year and leaves more work to be done in democratizing XR knowledge.

- European institutions (80%), and healthcare-related research (70%), have the highest rates of open access.
- Notably, funding correlates with citations: funded work is often more likely to receive higher visibility and citation counts. However, funded work also has a negative correlation with open access: papers supported by funding are less likely to be open access to a wider readership.

NOTES ON METHODOLOGY:

This section of the report utilizes knowledge mapping, also known as science mapping, which is a process that allows us to analyze and visualize the core features of publications on a specific topic (Chen, 2017[3]). This process reveals a number of important structural factors about a body of literature, including its intellectual and geographical parameters. Knowledge mapping also allows us to ask and answer questions like who the key authors are within the field of XR research and what are the prominent topics? What are the sources of funding and where is our knowledge geographically emanating from? When applied over time, knowledge mapping may also reveal paradigm shifts within a research field.

To create the knowledge mapping, certain parameters had to be set in order to obtain all relevant, peer-reviewed XR publications in English during 2025. This year the string query used in the Scopus database, accessed through the University of Pennsylvania on March 13, 2026, was further refined from last year to exclude 'VR' and 'XR' as search terms because they were yielding an increasing number of irrelevant results. Accordingly, the term 'extended reality' or 'XR' is broadly defined through the search query as encompassing papers that highlighted virtual reality, extended reality, augmented reality, and/or mixed reality within their title, abstract or keywords. The search parameters below yielded 11,025 articles:

TITLE-ABS-KEY ("virtual reality" OR "extended reality" OR "augmented reality" OR "mixed reality") AND (LIMIT-TO (PUBSTAGE , "final")) AND (LIMIT-TO (DOCTYPE , "ar")) AND (EXCLUDE (SUBJAREA , "BIOC") OR EXCLUDE (SUBJAREA , "IMMU") OR EXCLUDE (SUBJAREA , "PHAR")

3 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

OR EXCLUDE (SUBJAREA , "CHEM")) AND (LIMIT-TO (PUBYEAR , 2025)) AND (LIMIT-TO (LANGUAGE , "English")) AND (LIMIT-TO (SRCTYPE , "j"))

In addition, the University of Pennsylvania's ChatGPT Business was used to help analyze the large quantity of data for patterns and to create the graph images. ChatGPT Business does not retain data nor use it to train its models. Notably, ChatGPT Business was used to yield broader patterns and quantitative data, which were then checked and further analyzed by the author. ChatGPT Business was not used for any of the writing.

SOCIAL SCIENCE DEFINITION

According to the Scopus database, the following areas comprise 'social sciences':

3300 General Social Sciences
3301 Social Sciences (miscellaneous)
3302 Archaeology
3303 Development
3304 Education
3305 Geography, Planning & Development
3306 Health (social science)
3307 Human Factors & Ergonomics
3308 Law
3309 Library & Information Sciences
3310 Linguistics & Language
3311 Safety Research
3312 Sociology & Political Science
3313 Transportation
3314 Anthropology
3315 Communication
3316 Cultural Studies

3317 Demography

3318 Gender Studies

3319 Life-span & Life-course Studies

3320 Political Science & International Relations

3321 Public Administration

3322 Urban Studies

THEORIES IN XR, 2025

Maxwell Foxman, Shane Burrell

KEY TAKEAWAYS

- Core XR theories—presence, immersion, embodiment, cognitive load, cybersickness—are so entrenched that authors often use them without definition.
- Growth areas like medicine, HCI, spectatorship, haptics, and game design apply these classic theories in new contexts rather than replacing them.
- Fidelity and affect are mentioned but under-theorized, marking the clearest opportunities for future XR theoretical development.

By 2025, scholarly literature on virtual reality (VR), augmented reality (AR), and extended reality (XR) focuses on select theories. Presence, immersion, cognitive load, embodiment, and cybersickness were so ubiquitous in the journals we analyzed that authors often stated these terms with little or no definition. Most theoretical constructs receiving attention were field-specific, such as memory (Fukumori et al., 2025), or physical education (Amoroso et al., 2025). XR appears to be coalescing around a few key precepts embedded in its psychological impact (e.g., theories of presence and embodiment) and technical innovation (e.g., the Technology Acceptance Model), especially after a decade of relatively affordable commercial availability. Therefore, after summarizing these concepts, we will shift focus to how they are used and identify gaps for future theoretical development.

KEY THEORETICAL AREAS (PSYCHOLOGY, COGNITION, IDENTIFICATION, PHYSIOLOGY)

Much of the theory deployed across the 327 articles we reviewed in Presence, Virtual Reality, and particularly Frontiers in Virtual Reality paired key XR and subject-specific theories. These theories fell into roughly two categories. The first involved core psychological theories long attributed to XR: presence, or the feeling of "being there," that head-mounted displays (HMDs) can elicit (Lee, 2004); the concurrent sense of "immersion," which "refers to the ability of VR to engage users in multisensory stimulation" (Colombo et al., 2025); finally, theories of "embodiment" in virtual environments, or "the ensemble of sensations that arise in conjunction

with being inside, having, and controlling a body," (Kilteni et al., 2012, p. 374) were mentioned often with little explanation.

The second group of theories requires more detail, focusing on physiology, cognition, and identification. Nausea and dizziness stemming from "cybersickness" remain concerns. While various theories explain the phenomenon,[1] the authors this year notably relied on Sensory Conflict Theory, which "posits that cybersickness primarily arises from discrepancies between visual inputs and vestibular sensory feedback" (Rosanne et al., 2025). Cognitive load, or the idea that "human cognitive processing is heavily constrained by working memory, inhibiting learning when cognitive processing exceeds the learners' capacity" (Wyssenbach et al., 2025), was also tested; some studies combined it with related concepts such as "body ownership" (Archer et al., 2025). Theories like the Technology Acceptance Model (TAM) explained how and why identification occurs in virtual environments. The model posits four dimensions of technological adoption (perceived informativeness, ease of use, enjoyment, and behavioral intention) and has grounded studies of AR products like virtual "try-on" cosmetics (Micheletto et al., 2025).

These theories are commonplace in XR research, and their consistency highlights how core assumptions are cementing within the field. This is supported, tangentially, by this year's rise in PRISMA-guided reviews.[2] There is a consistent depth of research on immersive media (a term we use interchangeably with XR), which contains common research techniques, theoretical models, and subjects.

THEORETICAL DEVELOPMENTS (MEDICINE, HCI, SPECTATORSHIP, HAPTICS, GAME DESIGN)

Some areas of research saw increased theoretical development. Medicine remains a consistent focus, as one article invoked immersion and cybersickness in a study of critical thinking in health professionals (Stretton et al., 2025). Similarly, HCI theoretical development remains ongoing, given the continued need to articulate how users interact with three-dimensional, physical interfaces (e.g., Foxman et al., 2022). One scholar, for example, developed a framework for more ergonomic VR design this year (Tokatli, 2025), the sort of refinement to be expected.

1 See previous issues of Social Grammars of Virtuality for full explanation.
2 See more here: https://www.prisma-statement.org/

Games remain an evergreen subject, used to understand how XR components like locomotion or energy expenditure function in areas beyond entertainment, including the metaverse (Jo & Lee, 2025) and cycling (Colombo et al., 2025). Studies into gaming relied heavily on flow theory, which "suggests that deep immersion enhances gratification and engagement" (Jo & Lee, 2025, p. 221). This classic theory carries an inherent assumption: immersion from fully occluded environments can heighten flow.

One area that saw growth involved XR spectatorship. Studies focused on tourists and museum visitors, which we found more often in Virtual Reality than in the other two journals. These studies drew on a selection of theories to assess how viewing in the medium differs from other digital counterparts. Specifically, presence, immersion, and adoption models (e.g., TAM; Unified Theory of Acceptance and Use of Technology) were used to study different modalities of immersive presentation (Ariya et al., 2025), virtual visitor experiences of actual museums (Jangra et al., 2025), and reconstruction of historical sites (Yan & Du, 2025), among other subjects.

Access to haptic technology has become easier and more consistent, and researchers used it to study new modes of interaction, digital twins, and weight perception. For this work, theories of proprioception and haptic feedback were most invoked; a study applying haptic feedback in shoes used in virtual locomotion hypothesized the device would improve presence and, with it, proprioception or "the body's sense of position and movement" (Ataya et al., 2025, p. 158).

Thus, "classic" XR theories like immersion, presence, and embodiment are finding broader use within tangential areas of immersive media and providing more nuanced frameworks for addressing questions of interaction and consumption of the technology.

AREAS FOR FUTURE THEORETICAL WORK

This entrenchment, however, can also obscure areas of theoretical development that deserve more attention and are merely hinted at in the literature. Specifically, we will focus on two subjects: theorizing fidelity and affect. For each, we highlight examples of how they currently appear—and could appear—in future XR research.

Elsewhere, we have argued that *fidelity* offers a means of measuring and approximating reality against contemporary notions of truth in media production, especially given the ubiquity of computer-generated imagery (CGI) in society (e.g., Foxman, 2026). Immersive

media has been a bellwether of this phenomenon, given its close ties to gaming and the ease of displaying CGI-rendered images in HMDs. Fidelity was addressed in our corpus. For example, it was mentioned in evaluating the efficacy of avatars (Menzel et al., 2025), auditory presence (Mavridou et al., 2025), and notably VR-AI environments in classrooms (Tan et al., 2025). Collectively, these studies highlight the need to expand theorization of fidelity as an analytical tool and framework.

Similarly, affect, or "non-conscious experience of intensity" (Shouse, 2005), appeared numerous times in the corpus. In one study, trackers were designed to recognize users' affective states (Fourcade et al., 2025), while another explored emotional regulation via self-talk (Zisquit et al., 2025). These studies show affect is a vital avenue for measuring XR content's impact and users' connection to experiences, though there is room to expand the psychological and physiological understanding these studies rely upon. Affect theory has been deployed quite broadly as a heuristic beyond these limited categories, and we recommend attending to those other approaches, particularly regarding cultural (e.g., Anable, 2018) and social (e.g., Papacharissi, 2015) impact.

Beyond these two areas, novel and nuanced theorizing did occur. For example, Smith et al. (2025) began to theorize what the metaverse is to discuss ideas of consent within it. This type of theoretical work, along with the staid theories already mentioned, points to a new chapter in XR research. Much of the hype cycle that has dogged immersive media for a decade—tied to a few industry leaders—is fading as those companies abandon or shrink their investment. Moving past that cycle, theorists are meaningfully advancing how core XR components—HMDs, passthrough technology, haptics, and novel interaction modes—can be used in the years ahead with social and psychological effect, without being tied to any single vision of what XR can be.

ANNOTATED BIBLIOGRAPHY

We selected these five articles because they illustrate the range of theoretical work in this year's corpus—from conceptual models and consumer applications to nuanced treatments of engagement, consent, and embodiment—showing both how established theories travel across contexts and where new theoretical questions and framing can emerge.

Xionghui, L., Xiaoyu, Z., Jiaming, Q., Shuting, W., & Ping, D. (2024). "Fake it, you can touch it": a study of virtual touch effects based on VR technology. Virtual Reality, 29(1). https://

doi.org/10.1007/s10055-024-01092-y

This paper examines how virtual touch – reaching out and "touching" products with a virtual hand in an immersive VR shopping environment—shapes consumer psychology and evaluation. The authors ground their reasoning in the body model hypothesis, peri-personal space theory, and embodied cognition, arguing that virtual hand interaction can extend the felt boundaries of the body and recruit tactile mental imagery even in the absence of real haptic feedback. Across three studies using field, laboratory, and online experiments, they test how virtual hand touch affects sense of body ownership, haptic imagery, and product evaluation. The consistent finding is that virtual hand touch positively influences product evaluation, with body ownership and haptic imagery functioning as psychological mechanisms in that relationship.

Rubio-Tamayo, J. L., Gertrudix, M., & Wuebben, D. (2025). Immersive scientific communication: A multidimensional theoretical model for approaching Extended reality as a medium. Presence, 34, 135–157.

This conceptual article proposes a multidimensional theoretical model for using extended reality (XR) as a medium for scientific communication, arguing that XR's potential for engaging, complex, and immersive science content depends on communicators understanding it as a narrative and interactive form rather than merely display technology. The model works along three axes: it evaluates XR interface models, analyzes levels of reality and interaction, and identifies the dominant characteristics of immersive narrative. Rather than reporting an empirical study, the authors offer a structural framework intended to support the critical and reflective design of XR experiences, with particular attention to citizen-science projects where public participation and comprehension are central.

Jo, H., & Lee, J. K. (2025). Key drivers of user engagement in game-based metaverses: Enjoyment, escapism, reward, and spontaneity. Presence, 34, 219–241.

This empirical study investigates what motivates sustained engagement in game-based metaverses such as Roblox and Minecraft, drawing together Uses and Gratifications Theory and Flow Theory to model four user motivations—perceived enjoyment, escapism, reward, and spontaneity—as contributors to immersive flow and, in turn, to satisfaction and the intention to continue using a platform. Using partial least squares structural equation modeling (PLS-SEM) on responses from 160 users of various game-based metaverses, the authors find that perceived enjoyment is the strongest contributor to flow, while, contrary to

common assumptions, extrinsic rewards exert only minimal influence.

Smith, C. H., Molka-Danielsen, J., Webb-Benjamin, J.-B., & Rasool, J. (2025). The challenges of consent in a decentralised metaverse: exploring ethically informed protections and standards to safeguard humans. Frontiers in Virtual Reality, 6. https://doi.org/10.3389/frvir.2025.1401073

Seeking to understand the challenges of consent and what protections can safeguard humans in a decentralized metaverse, the authors start with a simple yet vital conceit: what is the metaverse? They explore the science fiction and web origins of the concept before defining the metaverse across both layers (physical, data link, network, transport, session, presentation, application) and ethical considerations (privacy and data security, identity and anonymity, digital divide, ownership and control, content moderation, mental and physical health). Finally, they highlight minimal, limited, and high levels of consent that appear across these layers.

Halbig, A., & Latoschik, M. E. (2025). The interwoven nature of spatial presence and virtual embodiment: a comprehensive perspective. Frontiers in Virtual Reality, 6. https://doi.org/10.3389/frvir.2025.1616662

The authors rightly highlight how spatial presence and embodiment are often treated as separate conceptual entities and instead broach how both ideas rely on perceptual and motor skills in VR systems, space and body perception, and virtual stimuli as a substitute for the real. Furthermore, each component's traditional "cues" affect each other reciprocally. They conclude with a useful table that highlights the ways by which common cues – specifically update rate, stereoscopic vision, field of view, visuospatial synchrony, visuomotor synchrony, head tracking, visuotactile synchrony and display type – impact both concepts.

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UNDERSTANDING TRENDS IN XR RESEARCH METHODS

Shravan Regret Iyer

KEY TAKEAWAYS

- XR research methods primarily center on empirical investigation, including experimental and quasi-experimental approaches to test the effectiveness of XR technologies. A growing number of XR experiments are incorporating tools such as EEG (the measurement of electrical activity in the brain), eye-tracking, and skin sensors to measure physiological responses.
- The representation of qualitative research methods (focused on data collection through semi-structured interviews, focus groups, thematic analysis, case studies, and critical analysis) is relatively small compared to studies employing experimental research methods. XR research could benefit from qualitative data – particularly to help guide researchers in understanding the 'how' and 'why' of human behavior, including technology use and adoption.
- Considering the advancements in AI that power XR technologies, including VR and AR, by offering computational intelligence for spatial mapping and content generation, future XR research could benefit from more ethics-oriented research, including studies of how XR can be conceptualized, governed, evaluated, and ethically adopted across a range of contexts.

Extended reality (XR) technologies, including virtual reality (VR) and augmented reality (AR), are witnessing rapid advancements. This is due to the large-scale adoption of artificial intelligence (AI), which is enabling faster hardware performance and machine learning to create immersive virtual environments for use in various fields such as education and training simulators in healthcare. This analysis examines trends in XR research methods, specifically, prevalent methods and those that are missing, multi-method use, and innovative research approaches. This analysis draws insights from over 300 peer-reviewed journal articles,

published in 2025, across three leading academic journals: 1) *Frontiers in Virtual Reality;* 2) *PRESENCE: Virtual and Augmented Reality*; and 3) *Virtual Reality*. This analysis also provides insights into how XR research focus is not limited to studying XR technologies themselves. However, it treats XR technologies as an active part of the research design, which is central to modern research methods, to investigate human phenomena.

OVERVIEW OF PREVALENT METHODS

Table 1

Distribution and prevalence of research methods used across the three peer-reviewed journal publications

Primary Method	Approx. No of studies		Examples of Methods
Experimental	~148	~45.2%	Randomized experiments, laboratory experiments, between-/within-subject comparisons, controlled condition manipulations, interface comparisons, physiological/behavioral experiments
Quasi-experimental	~40	~12.2%	Non-randomized interventions, single-group pre–post studies, training evaluations, educational interventions
Correlational	~37	~11.3%	Regression, structural equation modeling, predictor studies, associations, technology-acceptance models, individual-difference analyses
Systematic review	~27	~8.3%	Systematic reviews, meta-analysis, evidence synthesis
Qualitative	~22	~6.7%	Semi-structured interviews, focus groups, thematic analysis, stakeholder/expert interviews, phenomenological studies, qualitative case research
Conceptual & Action	~20	~6.1%	Delphi consensus, action research, theoretical frameworks
Mixed methods	~13	~4.0%	Quantitative surveys/performance measures combined with interviews, focus groups, observations, or thematic analysis
Case study	~10	~3.1%	Application case studies, case reports/series
Scoping/bibliometric	~10	~3.1%	Scoping reviews, bibliometric, narrative/comprehensive reviews

A closer look at the research corpus indicates that the prevalent XR research method primarily centers around empirical investigation, particularly experimental research. This is potentially due to XR studies situated within the fields of education, healthcare (rehabilitation and clinical applications), and professional training that require experimental evaluation and testing of the effectiveness of XR technologies. As part of the experimental investigation, XR researchers manipulate features of VR or AR and virtual environments to measure effects such as presence, emotion, well-being, mood, cybersickness, self-efficacy, and user

experience and engagement. One such experimental research method, in which researchers apply a treatment, is the randomized controlled trial. This method helps establish cause-and-effect while preventing unfair choices and keeping all groups in the study equal. An example of this approach is Diemer et al. (2025), who invited participants to a VR laboratory on-site and randomly allocated them to distinct experimental groups to compare the impacts of automated interaction in VR with human-led (experimenter-led) live interaction during emotionally relevant VR scenarios. Likewise, Galery et al. (2025) examined the acceptability and effects of a music-based VR intervention on emotion, well-being, and mood in geriatric outpatients, where the participants were randomly assigned to the intervention group, who engaged in an in-person, music-based VR experience, and the control group, where participants listened to traditional music with standard MP3 headphones.

Next, the published journal articles also feature quasi-experimental research methods, which test cause-and-effect relationships by manipulating independent variables without random assignment. As part of the quasi-experimental research method, XR researchers assess participants before and after an intervention without random assignment. Such a methodological approach can be seen utilized by XR researchers across various educational and clinical contexts. For example, Arezoomand et al. (2025) used quasi-experimental methods to evaluate healthcare and educational interventions involving hemodialysis patients. Other similar studies in the clinical context include: Keicher et al. (2025), who studied the impact of VR-simulation on medical student knowledge and learning experience; and Luciani et al. (2025) studied AR for upper limb rehabilitation with real-time kinematic feedback using HoloLens 2, which comprises infrared and depth-sensing cameras with numerous sensors for hand-tracking. In terms of limitations, the quasi-experimental research method has significant disadvantages, as it tends to have lower internal validity. It is potentially vulnerable to selection bias that skews results. Another side of the argument is that many practical applications cannot be studied under randomized conditions due to ethical and safety concerns, making a quasi-experimental approach indispensable for studying XR technologies.

The analysis of the research corpus also highlights how a growing number of XR experiments are incorporating tools like the EEG and skin sensors for physiological responses, i.e., to track brain waves and body arousal, stress, and perceived intensity of pain during the research experiment (Cass et al., 2025; Hori et al.,2025). Further, in terms of physiological and psychophysiological measurement, a range of studies have considered subjective responses alongside biological or neurological indicators to investigate arousal, cognitive workload,

engagement, stress, and attention. Such a methodological approach helps XR researchers understand and compare what participants say they experienced with the bodily or neural responses recorded during the investigation. One example is Al Sayyed & Al Azhari (2025), who conducted a controlled experiment in which they studied physiological responses, such as blood pressure and skin conductance, of subjects in an indoor environment using VR. Al Sayyed & Al Azhari (2025) used an eSense skin-response sensor to record participants' skin conductance and an automatic upper-arm blood pressure monitor to measure their blood pressure. Similarly, Hayati et al. (2025) examined inter-brain synchrony through EEG hyperscanning, comparing patterns of neural coordination during activities conducted in virtual and real environments. However, it must be noted that the use of biological or neurological indicators comes with challenges, including sensor accuracy, data stream synchronization, participant discomfort, and the interpretation of biological signals.

Another trend in XR research methods is the use of non-experimental correlational research, in which researchers examine statistical relationships among variables without manipulation. In particular, researchers have investigated how variables such as presence, engagement, cybersickness, competence, social influence, and usability relate to one another. For example, Llana et al. (2025) examined cybersickness and sense of presence as predictors of VR task performance, while Merz et al. (2025) examined how performance expectancy and social influence drive acceptance of VR technology for professional collaboration.

Further, XR researchers have used questionnaires and self-report measures to assess a range of topics, including presence, cybersickness, usability, self-efficacy, user experience, and engagement. For example, Levy et al. (2025) examined VR and celebrity endorsement and whether self-conversation with a sporting celebrity enhances later physical exercise. Levy et al. (2025) used questionnaires on body ownership, agency, and recognition, and participants in their study were asked to rate their levels of physical exercise both pre- and post-VR exposure.

The analysis of the research corpus also shows that self-report measures are combined with behavioral observations, task-completion outcomes, and interaction logs. For example, Archer et al. (2025) assessed the effect of arousal on performance in a VR narrative scenario using biological signals recorded via a medical-grade wireless Bluetooth wearable on the wrist, while also gathering survey data using a post-treatment, non-VR survey given to participants to assess their level of embodiment, perceived level of realism, and qualitative stress levels.

LACK OF QUALITATIVE AND CRITICAL RESEARCH METHODS

Speaking of qualitative research, across the three peer-reviewed journals, it is evident that the representation of qualitative research methods is relatively small compared to the studies employing experimental research methods. It is important to highlight that qualitative data in the form of semi-structured interviews, focus groups, thematic analysis, case studies, and critical analysis help guide in understanding 'how' and 'why' of human behavior, including technology use and adoption. An example of the qualitative method utilized in the research corpus is Amoroso et al. (2025), who explored the role of VR from a physical education teacher's perspective, particularly the experiences, challenges, and potential benefits perceived by physical education teachers across four European countries. Amoroso et al. (2025) collected data through open-ended focus group questions and analyzed the responses using thematic analysis. Such an approach offers a critical perspective on how individuals experience and evaluate XR technologies and provides insights not captured by quantitative methods.

Another important and critical research method that XR researchers can utilize more is case studies, which offer rich, complex details and in-depth investigations of real-world phenomena, similar to Pinto & Huertas (2025), who use real-world comparative case studies to explore two heritage sites in Spain.

FUTURE DIRECTIONS FOR XR RESEARCH METHODS

With advancements in AI technology at an unprecedented scale, the future challenges and implications of AI on XR are more concerning and evident than ever before, particularly surrounding the topic of ethics. For example, recent news (CBS News, 2026) showed the growing support from AI companies and their employees to slow down the development of AI due to the large-scale cyber incident (one of Open AI's models launched a cyber-attack without being prompted by a human and more than a thousand AI workers, including Anthropic CEO and Meta executives, signed an open letter supporting the slowdown) In this regard, future XR research could benefit from more ethics-oriented research, including studies of how XR can be conceptualized, governed, evaluated, and ethically adopted across a range of topics.

Further, in terms of research methods, investigations could adopt the Delphi method (Hasson et al., 2000) for structured expert consensus, where XR researchers could recruit

diverse experts to gather ethical concerns. However, it is important to consider some limitations of the Delphi method, including a slow, time-consuming research process due to multiple rounds of consultation. Further, in terms of the methodological approach, XR research could benefit from more qualitative, longitudinal, and ethnographic inquiry, in addition to the experimental approach, to study the socio-cultural and ethical implications of XR technologies. Such an approach could, in turn, guide advancements in XR around AI-enabled mixed reality, digital twins, and neuroadaptive haptics (which is an emerging field in XR that combines touch feedback with brain-computer interfaces) to understand the implications of XR and, more broadly, human-computer interactions and user-centered innovations.

Table 2

Hardware used for data collection across the three peer-reviewed journal publications

Hardware type	Research tools examples from the publications	Data gathered
VR head-mounted displays (HMDs)	HTC VIVE; Meta/Oculus Quest 2; other immersive VR HMDs	Head position/orientation, interaction behavior and task performance; also presents experimental stimuli
AR/MR head-mounted displays	Microsoft HoloLens 2	Hand tracking, head/eye movement, spatial interaction, upper-limb kinematics
Eye-tracking / pupillometry systems	Tobii Pro eye tracker integrated with HTC VIVE; HMD-integrated eye trackers	Gaze location, fixation, gaze entropy, pupil diameter, visual attention and scanning patterns
EEG systems	Brain Vision LiveAmp, two 32-electrode Ag/AgCl systems for hyperscanning	Electrical brain activity, frequency-band activity, neural synchrony and cybersickness-related neural responses
fNIRS systems	Functional near-infrared spectroscopy equipment	Cortical activation through changes in oxy-/ deoxyhemoglobin
Surface EMG systems	Surface electromyography electrodes/ sensors	Muscle activation, muscle effort, motor responses
ECG / heart-monitoring systems	Electrocardiography and heart-rate/HRV recording equipment	Heart rate, cardiac activity and heart-rate variability
Electrodermal / GSR sensors	Galvanic skin-response/electrodermal activity equipment	Autonomic arousal and physiological stress
Respiration / biofeedback sensors	Respiratory/breathing sensors integrated into biofeedback systems	Respiratory rate, breathing pattern and diaphragmatic breathing
Force plates / posturography systems	Force platform under the participant's feet	Center of pressure, postural sway and balance
Motion / kinematic tracking systems	HTC VIVE trackers; HoloLens hand tracking; headset/controller tracking	Gait, limb position, head/hand movement, step length, movement trajectories
Optical gait-analysis equipment	OptoGait	Step length, contact time, gait time and number of steps

Hardware type	Research tools examples from the publications	Data gathered
VR hand controllers	HTC VIVE controllers and other tracked VR controllers	Button presses, selections, hand position and interaction behavior
Oculography systems	PRET™ VR-based oculography headset (machineMD AG)	Clinical eye movements and oculomotor function
Electrical muscle stimulation (EMS) hardware	Single- and dual-muscle EMS electrodes/ stimulators	Provides controlled proprioceptive/haptic stimulation; responses then evaluated experimentally
Transcranial direct current stimulation (tDCS) equipment	ActivaDose direct-current stimulator with saline-soaked electrodes	Experimental neural stimulation rather than passive measurement
Cycling / exercise apparatus	Cycle ergometers and exercise-training systems used with VR	Exercise performance; combined with physiological recordings
Olfactory / multisensory apparatus	Scent-delivery setup for VR olfactory cues	Manipulation of smell during multisensory VR; behavioral/perceptual outcomes collected
Camera / computer-vision systems	Cameras, depth/vision systems, projector-camera calibration setups	Pose, tracking, spatial location, image fusion and movement information
Desktop monitors / conventional displays	Computer monitors, projection/display systems	Control/comparison stimuli, visual-performance tasks
Smartphones / handheld AR devices	Smartphones and handheld AR displays	Mobile interaction behavior and performance; sometimes used as the XR presentation platform

ANNOTATED BIBLIOGRAPHY

The following studies offer an innovative methodological lens to examine XR. They include work that assess presence as an objective measure through complex dynamical systems analysis, and a study that achieves group consensus and gathers expert insights via the Delphi technique to inform ethical and practical parameters for XR work. Together, these studies highlight the potential for XR development and the need for stricter regulatory guidelines and standards to govern XR technologies.

Gloeckler, S., Ford, T. J., & Biller-Andorno, N. (2025). Delphi study on the metaverse as an appropriate setting for mental health care: Conceptualization, opportunities, challenges, and conditions. Frontiers in Virtual Reality, 6. https://doi.org/10.3389/frvir.2025.1587316

Gloeckler et al. (2025), explored the metaverse as an appropriate setting for mental health care. They recruited 14 panelists from various research universities and clinical laboratories globally, who were identified through a literature review. The panelists, experts on the metaverse and mental health, came together to exchange ideas on appropriate care in the metaverse and to identify key challenges. Considering the limited academic literature on mental healthcare in the Metaverse, Gloeckler et al. used the Delphi technique, which relies

on repeated rounds of anonymous questionnaires to gather expert insights and achieve group consensus. Gloeckler et al.'s findings indicate that of the 27 original statements, all reached consensus by the third round, and an additional twenty new statements were generated based on suggestions from the expert panelists. In total, Gloeckler et al. identified 47 statements that reached consensus and highlighted the suitability of the metaverse as a setting for appropriate mental healthcare, while also identifying challenges to providing such care. For example, the group reached consensus on 'Providers

THE LANGUAGE OF XR: LOOKING BACK AT 2025

Katerina Girginova

KEY TAKEAWAYS

- XR is not one field linguistically. Rather, it is a set of parallel discourses, often describing the same technology in different ways and contexts.
- The most common word used to describe XR experiences and technologies is 'immersive'.
- Keywords like 'metaverse' peak in academic papers several years past their zenith in industry and popular discourse. This not only highlights the lag between research and publication time, but also that XR academic inquiry is highly driven by market developments.

INTRODUCTION

This section of the Social Grammars focuses on language. This includes the language and concepts we use to communicate about XR, and the introduction of any novel terms into our vocabulary toolbox. The logic behind this analysis hinges on the fact that language matters because it is the primary vehicle academic publications use to create an understanding of XR. On a methodological note, the analysis draws from three core journals dedicated solely to XR research: Frontiers in Virtual Reality (105 articles), PRESENCE: Virtual and Augmented Reality (24 articles), and Virtual Reality (178 articles). The annotated bibliography draws from three additional journals.

HOW RESEARCH COMMUNICATES XR

As the field matures, the findings show that a set of parallel discourses emerges from various domains like education, engineering, and medicine. While they often describe the same technology, they do so in different contexts and use varying terminology. For example, these terms appear in three different papers: 'immersive visualization', 'virtual environment' and 'immersive virtual reality'. As such, fields reuse ideas but not necessarily terminology.

Nonetheless, *immersive* emerged as the most common term used to describe XR technologies and experiences, across all domains. In fact, this year, the word *immersive*

appears in the title of roughly 1 out of every 4 articles across all of the journals, highlighting how central a term it is.

Still, the authors prefer adjectives over nouns; immersive over immersion. (As it turns out, many XR terms including *virtual reality* and *augmented reality* depend upon adjectives modifying nouns, which presupposes certain ways of thinking about the relationship between the digital and physical.) In addition, since adjectives describe a technology, they allow authors to forgo the more difficult task of defining core concepts like immersion. Subsequently, based on the 307 articles surveyed, we can more generally conclude that the use of XR-related adjectives is common, the employment of core XR concepts is less common, and the provision of any definitions, especially where nouns like *reality, immersion*, and *presence* appear instead of adjectives, is rare.

Another notable finding this year is the prevalence of research on keywords like the *metaverse*. While the metaverse peaked in corporate and popular parlance several years ago, it is not until this year that it reached its peak in academic publications, too. This not only reflects the temporal distance between academia/industry and research/publication, but also that XR research continues to be strongly influenced by commercial developments and interests.

Most of the papers analyzed apply XR to specific knowledge domains, like science communication. One such paper (Romero-Luis et al., 2025) is examined in more detail in the annotated bibliography below. In turn, XR scholarship and language naturally expand as they absorb the terminology of their applied contexts. Indeed, these linguistic evolutions tend to cluster around technical and experimental terms, which is partially a function of the specific journals examined. An example of this evolution as well as the introduction of *acoustic coherence*, a new linguistic concept in the toolbox of XR, can be seen in another paper in the annotated bibliography (Luberadzka et al., 2025).

Finally, the integration of additional senses into the XR experience, like haptics and acoustics, shows growth in the 2025 scholarship and the synergy between XR and AI is slowly beginning to yield research output, too. Indeed, language takes on added importance in the form of the large language models (LLMs) used to create XR experiences and we can hope that scholarship in the future critically examines this dynamic. The relationship between XR and AI is a space to watch closely and one possible route for its development, charted through public-facing discourse, may be seen in an important statement made at the

beginning of 2026 by the CEO of the XR Association (XRA)[4]: "XR is how AI meets the physical world", (LinkedIn Post, January 26, 2026[5]). Future research would also benefit from thinking more reciprocally about the role of language. For instance, this year, there were a number of papers that focused on advancing language learning through XR tools. However, none of these papers went as far as thinking about how our choices of language, in turn, shape XR.

ANNOTATED BIBLIOGRAPHY

Graves-Sandriman, E. K. (2025). Fiction references as framing devices in extended reality news discourse. *Public Understanding of Science, 34* (2), 204-221.

This article analyzes how fictional references are used as framing devices in news articles about extended reality technologies. The author examines 977 articles in mainstream UK news media between 2012-2017, or what represents the commercial boom period of extended reality technologies, and specifically VR. The author uses framing theory to examine how references to other popular fiction media—most frequently science fiction films—introduce extended reality technologies to a wide, and often unfamiliar audience, by drawing attention to specific facets of the technologies. Notably, the author discovers that while most of the science fiction references portray extended reality technologies in a dystopian light, the news coverage then employs them to paint a positive picture of extended reality technologies. Critically, the author notes that this framing largely supports the commercial interests of the companies creating the technologies yet also, perhaps unwittingly, undermines them by setting consumer expectations of XR beyond their realistic technical capabilities.

The author finds that almost a fifth of all articles include a reference to fiction, and often do so within the headline itself. The three most common fictional references are the Matrix, Star Trek and Star Wars, although they account for only about 7% of what is otherwise a broad range of media (primarily films, which include productions as diverse as Hook (1991), Who Framed Roger Rabbit (1988), and Top Gun (1986)). Ultimately, the diverse set of references, spanning over a century, speaks to different generations of audiences by giving them a frame of reference for interpreting XR.

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4 The XRA is based in Washington DC and is a trade association involved in shaping policy and public opinion around XR technologies.

5 https://www.linkedin.com/pulse/from-headsets-human-scale-systems-what-we-now-mean-xr-elizabeth-hyman-5xcce/

The primary purpose of the references is to explain XR to an unfamiliar audience. Nonetheless, the author highlights that the XR technologies depicted in the films and, subsequently, in the news articles are much more advanced than current XR technologies available on the market. In turn, this potentially sets unrealistic expectations and leads to consumer disillusionment with the technologies themselves. The author finds that the news article framing is also used to show how fiction is becoming reality and, to a lesser extent, to show dystopian futures of XR use.

Romero-Luis, J., Rubio-Tamayo, J. L., Sanchez-Acedo, A., Wuebben, D., & Codesido-Linares, V. (2025). Virtual, Augmented, and Extended Reality applied to science communication: A systematic literature review. *IEEE Transactions on Visualization and Computer Graphics*.

This paper systematically examines how XR technologies have been applied in science communication across 94 publications ranging from 2013-2023. The article contends that XR broadly, has the unique potential for simulation and experiential learning, which are particularly valuable qualities across several science communication theoretical frameworks: the public understanding of science, science engagement, and the science knowledge deficit model. In general, there has been an increase in the number of publications utilizing XR technologies to communicate scientific knowledge, with a peak in 2021.

"Immersive VR" is the key term and technology mentioned (appearing in 41 publications), with AR being the next most common (appearing in 21 publications). Notably, 12 articles examine more than one XR technology. The key uses of XR technologies for science knowledge dissemination were communicating ideas/concepts, disseminating information, and education/training. Notably, most of the studies have low sample populations and are based in university settings, which is a limitation. The authors also contend that analyzing conference papers and journal articles overlooks an arguably more important application of XR technologies for science communication, which is public demonstrations and more interactive mediums like video or virtual environments.

Luberadzka, J., Gusó Muñoz, E., Sayin, U., & Garriga, A. (2025). Audio technology for improving social interaction in extended reality. *Frontiers in Virtual Reality, 5,* 1442774.

This article introduces the concept of *acoustic coherence* to explore how audio

technology may facilitate more harmonious experiences in extended reality interactions. Furthermore, it posits that VR is a prime testing ground for audio algorithms aimed at enhancing communication. Acoustic coherence describes "a lack of plausible auditory illusion in mixed reality," (p. 2). This term is based on the more well-known concept of *coherence* in virtual reality user experiences, which describes the degree to which a digital environment behaves logically and consistently with its internal rules and reality. In turn, acoustic coherence emerges as an audio and spatially-based practice—the authors describe the nature of acoustic spatialization which must take place to render acoustic elements naturalistically in XR—which may enhance the user experience if done correctly. What constitutes the 'correct' acoustic experience in XR is a topic that requires more research, but current findings suggest that sub-optimal audio experiences, which include audio drag or are inaudible, impede user satisfaction in XR interactions.

The authors posit that VR provides a prime context for simulating real-life environments with highly controlled audio content, visual input, and head movements, providing a great platform for detailed testing of speech enhancement algorithms. While we know that our digital photographs are often, already visually altered or 'enhanced' by technologies like smartphones—sometimes without our explicit agreement—audio has been a less examined area of alteration. Nonetheless, while sound/hearing accounts for about 10% of our sensory input (the vast majority ~80% being dominated by sight), we perceive sound much faster than images, so it is important in shaping how we make sense of our other sensory data (Horowitz, 2012[6]).

Yang, F. C., Acevedo, P., Guo, S., Choi, M., & Mousas, C. (2025). Embodied conversational agents in extended reality: A systematic review. IEEE Access.

This article presents the first systematic review of embodied conversational agents (ECAs) within the context of XR. It examines 23 papers using the PRISMA convention to understand how ECAs are "designed, implemented and evaluated within immersive environments," (p. 79805). The results show that VR and CAVE-based interventions dominate the user experiences, along with life-size, human-like, female agents and neural-based conversation systems. The primary uses of ECAs within XR are for education or training, therapy, and social interaction.

Whereas language is a strong predictor of personality (including avatar or AI agent

6 Horowitz, S. S. (2012). The universal sense: How hearing shapes the mind. Bloomsbury Publishing USA.

personality), there is no standardized and widely adopted framework within XR for examining non-verbal communication such as facial expressions and body gestures. Notably, there are such efforts underway, but they are also quite controversial (Pykett, 2026[7]). Further, the authors find that most of the papers examine one-on-one interactions with ECAs at the expense of interactions with multiple ECAs and importantly, there is a lack of mention of ethics: "among the selected papers, we did not find an emphasis on privacy restrictions or ethical considerations in the design of XR ECAs," (p. 79821).should be required to inform users as to what is being tracked, for how long it is being stored, and any third-party with which it is being shared.' Another statement explored informing users when they are engaging with conversational agents controlled by AI engines. Gloeckler et al. contend that future research could expand to include policy makers and service users in the development and design of the metaverse for mental health offerings.

Harris, J., van den Berg, J., Cox, R. F. A., Van der Stigchel, S., & Nijboer, T. (2025). Complex Dynamical Systems Analysis as a Potential Measure for Presence. *PRESENCE: Virtual and Augmented Reality, 34*, 361–393. https://doi.org/10.1162/pres.a.10

Harris et al. (2025) emphasize the need for continuous, objective assessment of presence, as users perceive it as a subjective quality of the VR experience. In order to address this, Harris et al. (2025) highlight the need to approach the topic of presence through complex dynamical systems analysis and related data analysis techniques, including detrended fluctuation analysis, to capture and analyze the continuous stream of movement and time-series data. Harris et al. developed a virtual environment using the Unity 3D game engine for VR. They gathered three-dimensional positional coordinate data from the headset and two handheld controllers. Two experiments were conducted in which 34 participants experienced a VR game involving tossing colorful balls into designated baskets. Harris et al. examined coherence and immersion, both of which influence presence. In terms of the key takeaway, Harris et al. contend that complex dynamical systems analysis could be a solution to achieve continuous and objective measures, but highlight the need for validation in additional scenarios.

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7 Pykett, J. (2026). Governing Global Emotions: Technology and The New Science of Feeling.

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XR MARKET DEVELOPMENTS 2025

Kyle Cassidy

Despite false starts and uncertainty, the broad augmented and virtual reality (AR/VR) market continues to expand. 2025 saw an 18% year-over-year growth in the latest quarter, and forecasts project a 39% compound annual growth rate for the AR/VR headset market from 2025 to 2029[8]. Grand View Research put the 2025 global VR market at $129 billion and expects it will reach $164 billion in 2026—a projected increase of nearly 28%[9]. Head-mounted displays account for more than three quarters of the 2025 market share[10], although it's difficult to understand how wearables change that number, because several of those technologies overlap in reports. For instance, Grand View Research places the global XR-glasses market revenue in 2025 at $9.7 billion[11]. Nonetheless, AR remains the more widely used technology from the extended reality (XR) spectrum when accounting for global daily users on various phone apps like Snapchat.

META IS STILL DRIVING CONSUMER VR

Meta's dominance in the VR market (per Counterpoint research, Meta accounted for 80% of the stand-alone headsets sold in 2025[12]) means that its headsets will likely continue to play a key role—for better or worse—in academic research, too. Meta has also worked diligently on directly extending its dominance in academic and educational markets. In February 2025 Meta officially launched its Meta for Education program in partnership with thirteen colleges and universities across the U.S. and the UK[13]. Meta for Education is modeled on Meta for Business, with the goal of delivering education apps as well as Meta Horizon

8 International Data Corporation, June 2025, https://my.idc.com/getdoc.jsp?containerId=prAP53608225

9 Grand View Research, June 2026 https://www.grandviewresearch.com/industry-analysis/virtual-reality-vr-market

10 https://www.grandviewresearch.com/industry-analysis/head-mounted-display-hmd-market

11 https://www.grandviewresearch.com/horizon/statistics/augmented-reality-market/smart-glasses/xr-glasses/global

12 September 2025 https://counterpointresearch.com/en/insights/global-vr-headset-market-in-h1-2025

13 February 2025 https://about.fb.com/news/2025/02/new-meta-education-offering-generally-available/

Managed Solutions, a set of headset management tools, to educators. However, trying to manage multiple headsets in a lab environment has been a challenge with Meta's platform since its inception. This has been mirrored by internal turmoil, too: Meta offered a lifetime license for Horizon Managed Solutions for $100 per device and then ended the service in February of 2026.

In addition, Meta seems committed to pursuing a mass market through its strategy of lower-end VR headsets, content, and pricing points, but that often disgruntles their original customer base. This strategy was further exemplified by John Carmack, the former CTO of Oculus under Meta's control of the company, who got into a fight on social media with some of his followers—hardcore virtual reality enthusiasts. In short, Carmack stated that Beat Saber (the low-end, highly popular VR game) was far more important for Meta than Half-Life Alyx[14] (another popular, but much higher-end VR game). This led to debates over the future of VR. Specifically, for hardcore VR enthusiasts who'd been brought up in the powerfully immersive early years of the technology this felt like film scholars being forced to watch reality TV.

Still, Meta's pursuits of a broader market base are often met with deployment issues, too. For instance, in October 2024, Meta released the Quest 3S, a less capable version of the Meta Quest 3. The 3S had half the memory, lower resolution, significantly fewer pixels per inch, a diminished field of view, a larger form factor, and a smaller battery. In every regard, apart from a lower price, it was a step back from their previous models. The release was plagued by various software issues in 2025 and led to many disgruntled customers and discounts on the headsets across stores.

PC VIRTUAL REALITY, GAMING, AND HIGH-END HEADSETS

Meta's retreat from high-end experiences in software and hardware leaves the door open for innovation and for other companies to step in. In addition, Nvidia's RTX 50-series and AMD's Radeon RX 9000-series graphics cards now give a significant boost to PC-VR, and with the release of Epic's Unreal Engine 5.6, XR workflows got easier. There are new VR templates for locomotion, grabbing and interaction, as well as steps towards standardizing how VR development works. This allows for easier co-authoring of standalone and PCVR

14 February 2025 https://www.uploadvr.com/john-carmack-pc-vr-is-a-boutique-niche/

experiences, enabling developers to write for PCVR targets like 120 FPS high fidelity rendering.

Some of the other companies that have entered the market include Shiftfall MaganeX superlight 8K headset ($1,899) and the Pimax Dream Air headset ($1,999). See below for comparison between some 2025 headsets.

Headset	Type	U.S. price	Weight	Display	Resolution per eye	Refresh rate	PC
Meta Quest 3	Standalone and PCVR	$499.99 at launch; $599.99 for current 512GB model	515 g	LCD	2064 × 2208	Up to 120 Hz	PC optional for PCVR
Shiftall MaganeX Superlight 8K	PCVR	$1,899	Under 185 g	10-bit Micro OLED	3552 × 3840	90 Hz	PC required
Pimax Dream Air	PCVR	$1,999 starting price	Under 170 g	Sony Micro OLED	3840 × 3552	90 Hz	PC required
Bigscreen Beyond 2	PCVR	$1,019 starting price	107 g	Micro OLED	2560 × 2560	90 Hz	PC required

Another notable company to watch is Virtuix, who added a number of new titles to their Omni One VR treadmill platform, bringing the total to more than 50. The Omni One allows users to physically walk and run in any direction, replacing thumbstick locomotion. The 360° treadmill bundles with a Pico 4 Enterprise headset for about $2,500 and reported sales of more than 1,000 units[15].

SMART GLASSES ARE (ONCE AGAIN) THE NEXT BIG THING IN XR

In a 2024 Q4 earnings call to investors, Mark Zuckerberg said that the company's Reality Labs had lost nearly five billion dollars but that "our Ray-Ban Meta AI glasses are a real hit, and (2025) will be the year when we understand the trajectory for AI glasses as a category[16]." This enthusiasm led Meta to invest a reported $3.5 billion in Essilor Luxottica, owner of Ray-Ban and Oakley. Meta also launched the genderneutral HSTN (pronounced HOW-stun) smart glasses with Oakley, which retail for about half of what the Ray Bans do with better video capture.

Indeed, the smart glasses market grew significantly in 2025, with Meta as the clear

15 February 2025, https://virtuix.com/blogs/news/omni-one-game-library-expands-to-55-titles-including-arizona-sunshine-and-into-the-radius

16 January 2025 https://s21.q4cdn.com/399680738/files/doc_financials/2024/q4/META-Q4-2024-Earnings-Call-Transcript.pdf

market leader. Competitors include HTC, Alibaba, Rokid, and Amazon who also launched entries, signaling broader industry commitment to the category. Broadly the smart glasses fall into two categories: Camera + AI assistant, or AR Overlay / Heads Up Display. The first category, camera + AI assistant glasses (such as the Meta Ray Bans) prioritize hands-free photo and video capture paired with a voice assistant for answering questions or interpreting what the camera sees. The second category, AR Overlay or Heads-Up Display glasses (such as some HTC and Rokid models) project visual information onto the glasses themselves, allowing the wearer to see text and video. In both cases there are plenty of places where AI seems an obvious fit: Procedural generation of detailed open-world maps, using NeRF to reconstruct 3D scenes from 2D images, creating dynamic and adaptive environments, or voicing NPCs.

Nonetheless, civilians quickly stumbled upon the capacity of these technologies to surveil: to see, identify, record and act at a distance, most often without consent. This led to a downpour of negative press, particularly aimed at Meta, resulting in a pledge from Meta to release smart glasses without cameras, and to curtail the capacity of some current units with cameras[17].

MYTHICAL NAMES AND GOVERNMENT CONTRACTS

Another booming business area for XR is government defense contracts. Oculus cofounder Palmer Luckey's military technology company Anduril (named after Aragorn's sword in Tolkien's Lord of the Rings novels), demoed "EagleEye", an augmented reality headset co-designed with Meta[18]. The headset will allow military personnel to watch drone video, use night vision and track friendly forces. In competition for the military contract for the Soldier-Borne Mission Command (SBMC) prototype is Rivet[19], backed by Palantir (named for Aragorn's remote-communications crystal ball in Tolkien's Lord of the Rings novels.)

Meanwhile, in August 2025, Finnish XR company Varjo (which means "shadow" in Finnish) announced a partnership[20] with defense contractor THEON (which means "God" in

17 September 2026, https://www.reuters.com/business/meta-expected-unveil-smart-glasses-without-camera-privacy-concerns-grow-2026-09-23/

18 October 2025, https://www.anduril.com/news/anduril-s-eagleeye-puts-mission-command-and-ai-directly-into-the-warfighter-s-helmet

19 September 2025, https://www.defenseone.com/defense-systems/2025/09/anduril-and-palantir-backed-startup-rivet-go-head-head-soldier-virtual-display-competition/407960/

20 August 2025, https://varjo.com/news/varjo-welcomes-theon-as-strategic-investor-to-accelerate-mili-

Greek but is also a George R. R. Martin character) to develop military XR solutions. Their XR-4 headsets for military simulation training were released in October of 2025. The US military had previously used Varjo's XR-3 to train helicopter crews. Similar technology was used in 2023 to train Ukrainian pilots in how to use their new US F-16 fighters.

PERSISTENT WIDGETS… ARE THE KILLER APP?

Lastly, in 2019 Gabriel René and Dan Mapes published *The Spatial Web: How Web 3.0 Will Connect Humans, Machines and AI to Transform the World*, which predicted digital objects could have real world coordinates and semantics—not just where they are in space, but what they are and how they relate to other objects. This has long been the case in AR games like Pokémon Go, where the user's cell-phone provides a view into an artificial world mapped over the real one. In 2025 Apple's rollout of Persistent Widgets is another step toward more concrete, real world cases where users can place digital items (calendars, grocery lists, memos, images), in specific, static places in the physical world and then view them through XR glasses[21]. The idea would allow users to essentially place a large number of virtual objects in their living and working spaces and interact with them when wearing their Vision Pro headset. There is also the possibly that different items could be visible to different people: i.e. a palette of items could be tagged with overlaid labels that might appear differently to a warehouse worker, a dock worker, or a truck driver, depending on what that person needed most to know or see. This is an interesting idea and possibly AR's eventual killer app, although right now, having to wear one's Vision Pro headset all day makes it impractical.

tary-grade-vr-xr-innovation

21 June 2025, https://www.apple.com/newsroom/2025/06/visionos-26-introduces-powerful-new-spatial-experiences-for-apple-vision-pro/).

HOW WEARABLE SENSORS ARE SHAPING THE FUTURE OF IMMERSIVE TECHNOLOGIES

Youngjun Lee & Sanghoon Kim

KEY TAKEAWAYS

- Immersive technologies are becoming body-aware. Sensors that track muscle signals, eye movements, heart rate, and skin conductance are increasingly built into XR devices, turning headsets and smart glasses into platforms that can detect and respond to what is happening inside the user's body in real time.
- Real-world applications are taking shape. Biosensor-enhanced XR is moving beyond experimental research into sport, health care, mental health, and education — enabling systems that adjust exercise intensity based on heart rate, visualize patient data during surgery, and adapt relaxation programs to a user's stress levels.
- The sensitivity of the data demands new safeguards. Biometric signals collected by XR systems can reveal personal identity, emotional states, and health information, often beyond what users realize. As these systems reach broader populations, including children and patients, privacy-by-design and robust data governance will be essential.

INTRODUCTION

As Extended Reality (XR) systems are increasingly combined with wearable biosensors, immersive technologies are moving beyond visual displays toward experiences that respond to the body in real time. These sensors can track physiological signals such as heart rate, electroencephalography (EEG, a technique for recording electrical activity in the brain), respiration, and skin conductance (a measure of stress-related arousal), while advances in hardware, software, connectivity, and processing power are making biosensor-XR systems more feasible for real-world use. This convergence is beginning to shape practice across medicine, sport, and related fields, expanding beyond consumer wellness and engagement into areas such as monitoring, rehabilitation, training, and decision-making. In medicine, Stanford Medicine has reported using Apple Vision Pro to display patient vital signs during

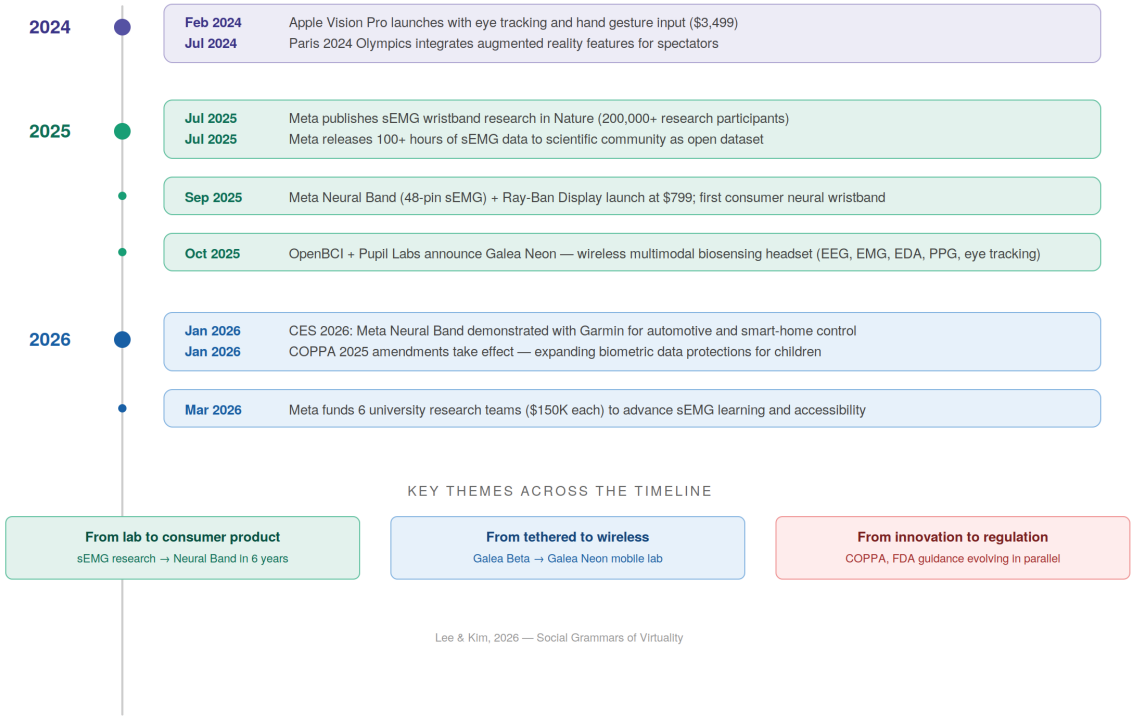
procedures (Pitsiladis, 2023). In sport and live-event contexts, augmented reality (AR) glasses are being developed to provide real-time performance metrics, and spectators at the Paris 2024 Olympics were offered AR features through the official Olympic digital experience (*Olympic Digital Experiences Set to Serve and Delight Fans for Paris 2024*, 2024).



The importance of this convergence lies not only in technological advancement but also in its growing practical relevance. By connecting real-time bodily data with immersive environments, biosensor-integrated XR systems create new possibilities for feedback, assessment, training, rehabilitation, and decision-making. More broadly, they create new means for being in and engaging with the world. For instance, biosensors have been used in virtual reality (VR) communication simulations to quantify stress responses and evaluate training effectiveness, while AR-based safety training has been shown to improve spatial awareness and procedural performance in high-risk settings (Baghaei et al., 2022; Ban et al., 2024; Ismael et al., 2024). However, these examples also suggest that real-world adoption will require more than technical feasibility. As biosensor-XR systems enter applied settings, their promise

must be supported by careful validation, usable design, workflow fit, and responsible data governance. Considering these opportunities and challenges, this special section highlights recent trends in wearable biosensor-XR convergence, examines applications across multiple domains, and discusses the growing importance of validation, data governance, usability, and real-world workflow integration, with U.S.-based developments and regulatory contexts considered where relevant.

Figure 2. Timeline of Key Developments in Wearable Biosensor–XR Convergence (2024–2026)



TECHNOLOGICAL CONVERGENCE OF WEARABLE BIOSENSORS AND XR

Using Muscle Signals to Control Immersive Devices. One major development in this space was Meta's investments in wrist sensors that detect muscle signals as input methods for augmented reality experiences. In July 2025, Meta published a seminal paper in the Nature journal describing how signals from sEMG wristbands could identify nuanced finger and

hand gestures based on electrical activity generated by muscle contraction in the wrist and forearm (*New Reality Labs Research on Wrist-Based sEMG for Human-Computer Interaction Published in Nature*, n.d.-a). Unlike camera-based hand-tracking systems, which are affected by occlusion, poor lighting, and subtle gestures, wrist sEMG can capture electrical signals from muscles and nerves that represent signals the body sends before or during movement and potentially enable the detection of intention prior to movement onset. In the Nature study, the authors showed that off-the-shelf sEMG decoding models trained on datasets from thousands of people, such as a handwriting corpus of 6,627 participants, worked accurately for new users without requiring individual setup or calibration. Incorporating an additional 20 minutes of person-specific personalization increased median handwriting performance by 16% (heathera, 2025; Kaifosh & Reardon, 2025)

Meta's Neural Band contains 48 electrode pins, organized into 16 bipolar sEMG sensing channels. Product and help documentation state that the band supports swipes, double-tap or click-like gestures, pinch-and-roll controls, and drawing with neural handwriting on a surface (New Reality Labs Research on Wrist-Based sEMG for Human-Computer Interaction Published in Nature, n.d.-b). Meta's earlier wrist-haptics research also explored how wrist-worn haptic devices could support interactions with virtual buttons, textures, and virtual objects (isolomons, 2021)..

Eye Tracking as Biometric Infrastructure. Over the past decade, eye-tracking solutions have evolved from specialized research instruments to standard features on consumer and enterprise XR headsets. The Apple Vision Pro, announced in June 2023 and launched in the United States in February 2024, uses eye gaze, hand gestures, and voice as primary inputs; eye gaze is used by looking at UI elements and tapping a finger to select (Adhanom et al., 2023; *Introducing Apple Vision Pro, n.d.; Learn Basic Gestures and Controls on Apple Vision Pro*, n.d.). Eye tracking is also used with the Quest Pro to display the sharpest image where the user is looking and to enable features that make avatars feel more natural in social interaction, such as expressive avatar eye behavior. Varjo XR-4 has been marketed for enterprise and research use cases that benefit from gaze tracking, offering up to 200 Hz. Enterprise and research applications include high-fidelity XR for training and simulation, ergonomics, and human-machine interaction research (*Eye Tracking*, 2026; *Presence Platform Introduces New Developer Tools for Meta Quest Pro*, n.d.). Platforms like iMotions enable researchers to sync VR eye tracking with other physiological and behavioral measures, such as EEG, EDA/GSR,

ECG, and facial expression analysis, within a system that records different body signals at the same time, allowing combining several types of data, such as eye movement, heart rate, and skin response in VR (*iMotions Lab - Human Behavior Research Platform*, 2025). One of the leading commercial vendors of XR eye-tracking systems is Tobii, whose technology powers headsets like the PlayStation VR2, Pimax Crystal, and Play For Dream MR. Notably, Tobii's eye-tracking technology extends well beyond XR, it is widely used in automotive driver-monitoring systems that detect drowsiness and distraction, illustrating how gaze sensing is becoming a broad biometric infrastructure across industries. In its official XR resources, Tobii describes eye tracking not as an input mechanism but as an enabling technology for XR, capable of displaying the sharpest image where the user is looking, attentive interfaces, and lifelike emotional and social signals in real time (*Eye Tracking — a Catalyst for Innovation in AR, VR, and MR*, n.d.).

Physiological Monitoring: Heart Rate, HRV, and Skin Conductance. Beyond muscle-signal wristbands and eye tracking, a third category of sensors is making its way into XR: cardiovascular and electrodermal sensors. Heart rate variability (HRV) refers to the variation in time between heartbeats and is a commonly used noninvasive measure of how the nervous system regulates the heart. HRV can be measured using ECG-based chest straps or estimated from light-based sensors found in many smartwatches, a technique known as photoplethysmography (PPG). HRV has been employed in applied settings as an indicator of physiologic stress and recovery, and higher resting HRV, associated with parasympathetic nervous system activity, has typically been associated with improved emotion regulation (Shaffer & Ginsberg, 2017)called interbeat intervals (IBIs. Since objective biosensor streams from consumer wearables like Oura Ring Gen 4, WHOOP, and Garmin Watches, compatible with HRV analysis, are becoming widely available and usable (generally recorded overnight via PPG and validated against ECG to some extent), HRV-derived metrics can now be paired with XR devices to enable biofeedback and even systems that adjust automatically based on the user's body signals (Dial et al., 2025; Jamieson et al., 2025). Research using in-headset inertial sensors from commercial VR headsets has demonstrated that heart and respiratory rates can be estimated from head micro-motions driven by the heartbeat (Floris et al., 2020)with embedded micro-electromechanical systems, have the potential to assess the mechanical heart's functionality and respiratory activity in a non-intrusive way and without additional sensors by utilizing the ballistocardiographic principle. To test the feasibility of this approach

for opportunistic physiological monitoring, thirty healthy volunteers were studied at rest in different body postures (sitting (SIT. Skin conductance, a measure of stress-related arousal, such as electrodermal activity (EDA) sensors (found on research wearables like the Empatica E4), measure fluctuations in skin conductance caused by eccrine sweat-gland activity (Milstein & Gordon, 2020). EDA sensors are commonly used to measure stress-related body activation. EDA signals have been used in XR/VR research to infer affective states, monitor arousal, and deliver adaptive experiences, for example, adjusting VR relaxation environments based on real-time stress levels, or monitoring trainee anxiety during simulated medical procedures (Halbig & Latoschik, 2021).

Multimodal Integration: The Convergence Platform. OpenBCI's Galea is one of the best-known multimodal biosensing platforms built specifically for XR research. As part of Varjo, Galea included EEG, EMG, EDA, PPG, EOG, and eye tracking, all within a headset. All sensors were driven by the same hardware clock, enabling easy collection of synchronized brain, muscle, skin, cardiac, and gaze data (*Combining VR and Neurotechnology with OpenBCI's Galea*, n.d.-a). On October 1, 2025, OpenBCI and Pupil Labs announced Galea Neon, a wireless configuration that pairs the Galea Beta biosensing platform with Pupil Labs' Neon eye-tracking system. OpenBCI and Pupil Labs claim researchers can transition between VR, XR, 2D screen-based, and real-world controlled experiments without changing hardware, while maintaining time-aligned EEG, EOG, EMG, EDA, PPG, and eye-tracking data streams (*OpenBCI and Pupil Labs Announce Launch of Wireless, All-in-One Brain, Body, and Eye Tracking Headset - Pupil Lab**s***, 2025a). Early work by Galea suggests several potential areas of convergence for XR-enhanced biosensing, including affective computing and simulation/training, user-state monitoring, and medical research applications (*Combining VR and Neurotechnology with OpenBCI's Galea*, n.d.-b; Neurojoe |, 2023). Galea's platform evolved from a tethered, Varjo-based XR platform to a wireless, mobile deployment. This eventually resulted in Galea Neon, which enables synchronized multimodal biosensing data capture across VR/XR, 2D screen-based, and selected real-world workflows (*OpenBCI and Pupil Labs Announce Launch of Wireless, All-in-One Brain, Body, and Eye Tracking Headset - Pupil Labs*, 2025b).

EMERGING APPLICATIONS ACROSS DOMAINS

Understanding potential uses of wearable biosensors in XR helps clarify why this convergence matters. Recent studies have begun to introduce biosensor-enhanced XR in

specific contexts, such as exercise, rehabilitation, mental health, and training, moving beyond proof-of-concept research. Applied uses within sport and exercise may be the most obvious developments. Exercise technology has used XR to boost engagement and interest while allowing for more individualized feedback. One review demonstrated XR exergames being used with increasingly diverse populations and contexts for physical activity promotion/intervention, rehabilitation, and cognitive and psychological support and maintenance (Lampropoulos et al., 2025). At a smaller scale, BioVR demonstrates where the field could go: a previous study (Zhao et al., 2025) outlined a biofeedback-driven adaptive virtual fitness system designed to maintain personalized exercise intensity by integrating users' physiological data into the VR environment. Together, these developments suggest that XR exercise systems are shifting from simple gamification toward physiologically informed adaptation.

The adoption of these systems in health care and rehabilitation is beginning to appear in both procedural medicine and motor recovery applications. Researchers at Stanford Medicine recently published a study in which they used the Apple Vision Pro during an atrial fibrillation ablation procedure. The device was used to see and interact with multiple streams of real-time data within the physician's field of view, demonstrating the potential utility of spatial computing for displaying key information during surgery or procedures (Armitage, 2024). One recent study (Amin et al., 2025)which pose challenges for sustaining enduring improvements. The immersive virtual reality (VR found that immersive VR-based hand rehabilitation games enhanced hand motor outcomes in 52 patients with subacute stroke. Notably, participants randomized to the experimental group showed greater clinical gains and better maintenance of performance at follow-up. This study also correlated electromyographic features with clinical outcome measures. These findings may help establish how biosensors can be leveraged not only for intervention delivery but also for more objective monitoring of recovery.

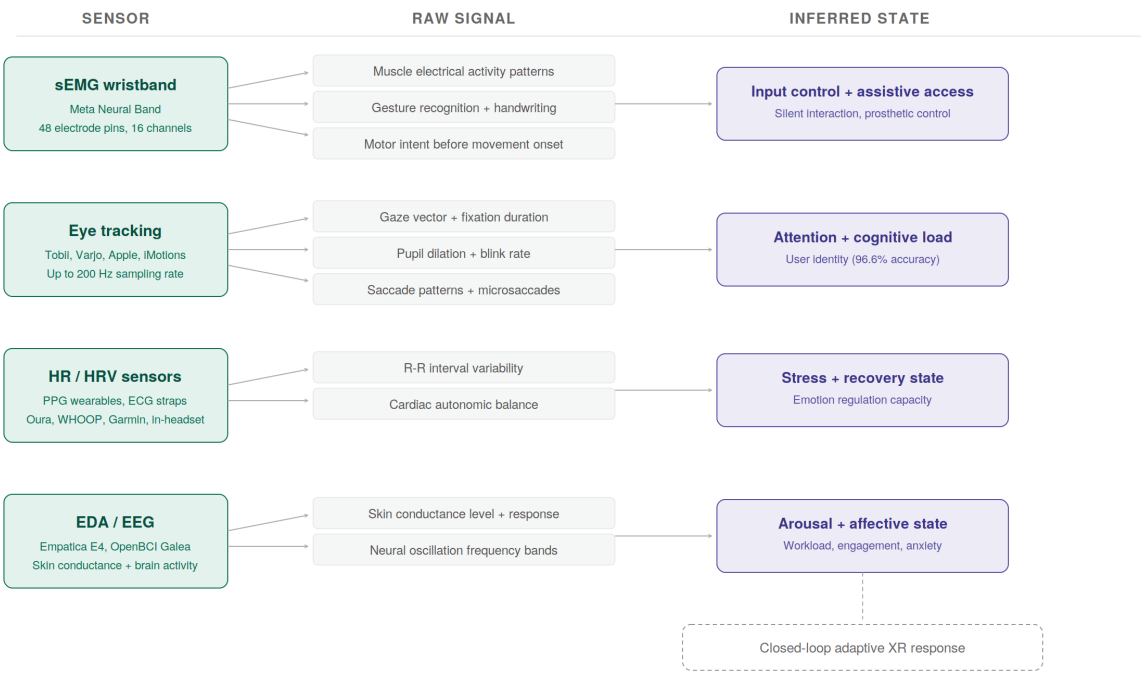
Mental health and stress regulation are other areas of application ripe for development. One previous study (Chittaro et al., 2024) found that a VR relaxation application with real-time biofeedback on breathing, skin conductance, and heart rate produced greater relaxation and presence effects than a placebo biofeedback condition. One of the recent studies (Baldini et al., 2024)biofeedback (BF similarly described HRV- and electrodermal activity-driven VR biofeedback sessions that resulted in decreased perceptions of state anxiety, with particularly promising psychophysiological results when biofeedback was based on skin-conductance data. These works hint at the potential for XR to expand beyond offering static relaxation content and toward adaptive programs that can adjust to users' mental and physical states

in real time.

In education/training, biosensors are being utilized to assess how immersive systems impact attention and cognitive load. In a 2025 study of 74 nursing students, previous researchers (Adler et al., 2025)but its impact on declarative and procedural knowledge outcomes remains unclear. This study utilises a multimodal approach, combining self-reports with data from psychophysiological sensors. Objectives The study aims to evaluate how different levels of immersion in VR—high-immersive VR (head-mounted display, HMD-VR used eye-tracking and an EDA sensor during VR-based learning and found that, while both groups improved in knowledge outcomes, the highly immersive head-mounted VR group exhibited higher cognitive load during procedural tasks. These findings are critical because they demonstrate how biosensors in XR can be leveraged not only for outcome/user performance metrics but also for XR design and calibration to better train individuals.

IMPLICATIONS FOR PRACTICE AND INDUSTRY

Figure 3. From Sensor to Insight: How Biosensors Generate Actionable Data in XR



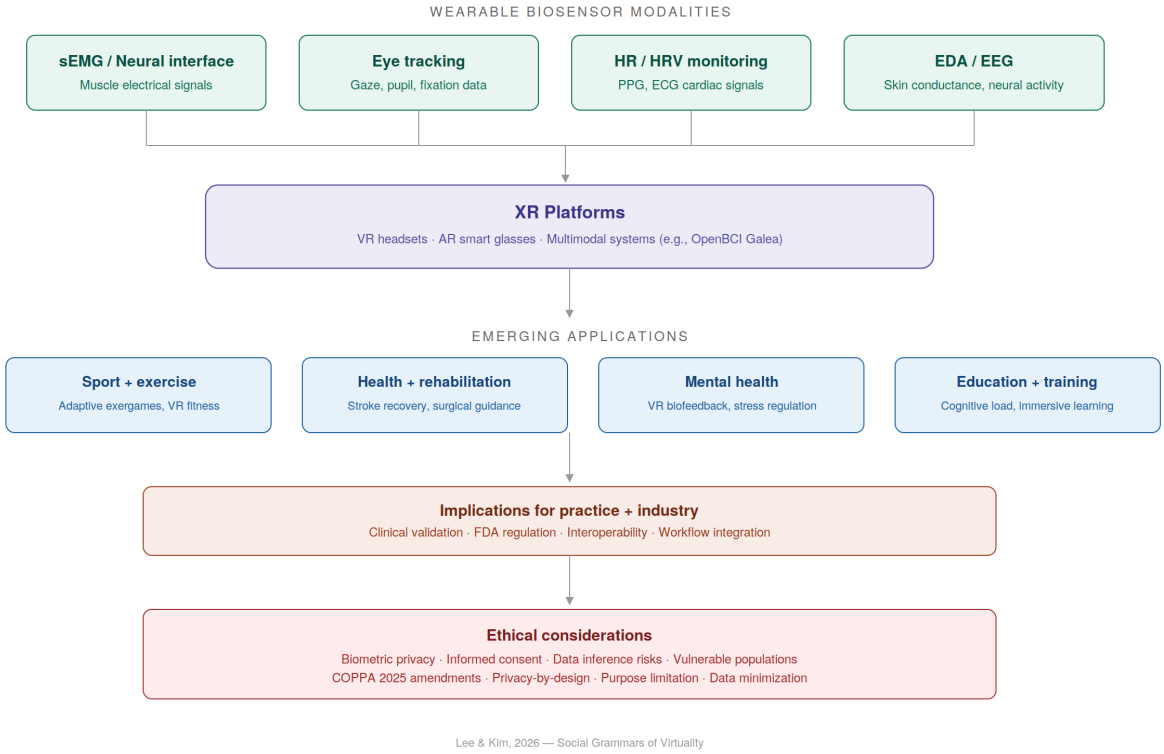
Lee & Kim, 2026 — Social Grammars of Virtuality

As biosensor-integrated XR moves beyond research demonstrations and towards real-world implementation, clinical utility and widespread use will likely depend less on technical innovation than on clinical relevance, usability, and workflow integration. For clinicians, therapists, coaches, and instructors, the important question will be if and how biosensor outputs can be leveraged to provide actionable information that improves assessment, feedback, safety, or decision-making within existing practice routines. Recent implementation in science XR work suggests that, beyond efficacy, successful clinical deployment will require attention to safety, technical requirements, institutional/structural demands, provider factors, and reimbursement processes (Morgan et al., 2025a)which includes both Augmented Reality (AR. Likewise, rehabilitation research centered on stakeholder priorities has found that end users commonly value simplified navigation, adaptive input modalities, and assessment capabilities that enable clinically meaningful measurements, rather than highly featured systems that may be cumbersome (Elor et al., 2026) engaging participants [N = 24 total including ten clinicians, eight patients, three designers, and three engineers] across five focus groups with stakeholders from clinical, academic, and industry settings. Through structured

usability testing and a four-axis framework analysis, we evaluated immersive Virtual Reality (VR.

These results also suggest to developers and platform designers that interoperability and trustworthy data governance should be central, not afterthought considerations in design. The FDA defines interoperability as "the ability to both exchange and use information safely, securely, and effectively between medical devices and systems." The FDA further states that interoperability "can lead to improved patient care, fewer errors, and greater innovation." (Health, 2024) However, reviews and policy reports are also clear that immersive systems introduce significant privacy and cybersecurity risks, including the potential for sensitive personal or health information to be revealed through XR data use (Fagan & Gilbert, 2025; Lake et al., 2024).

Figure 1. Conceptual Framework: From Wearable Biosensors to Ethical Governance



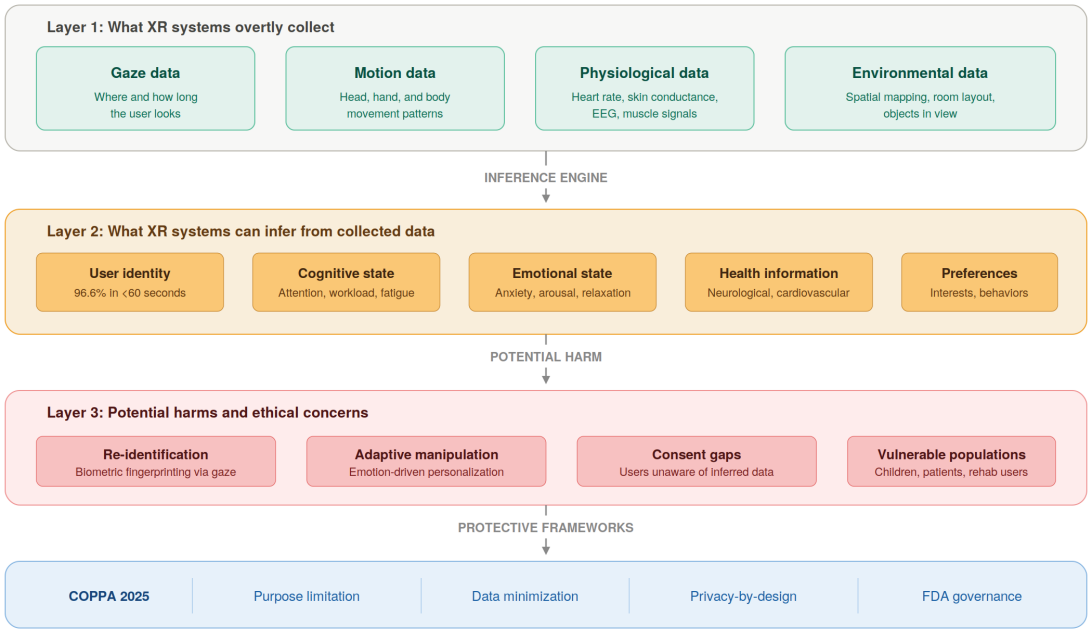
From an industry perspective, one key takeaway from this report is that commercialization will likely hinge on validation, regulation, and integration. According to FDA guidance materials, sensor-based digital health technologies "already embrace FDA authorized wearable devices

that are non- or minimally invasive… that can be used for continuous or spot-check monitoring… and support use in nonclinical settings outside of the hospital or clinic (e.g., at home)" (Health, 2026). Taken collectively, these trends indicate that as XR-biosensor systems transition from consumer-based wellness and engagement claims to data collection for monitoring, rehab, and other use cases, we will likely see increased emphasis on validation, governance, and integration across the digital health ecosystem (Health, 2026; Morgan et al., 2025b. In this regard, the future of wearable biosensor XR will be determined not just by technological advances in hardware but also by whether these systems can prove trustworthy, usable, and valuable at scale.

Although this report has focused on sensors, XR platforms, and real-time feedback rather than artificial intelligence, AI is likely to become increasingly important in this space. As XR systems collect richer streams of gaze, movement, heart rate, and skin response data, AI models can be used to detect user states, personalize feedback, and adapt immersive environments in real time. This will also raise new questions about transparency, bias, explainability, and accountability, particularly when AI-generated interpretations are used in health care, rehabilitation, education, or mental health contexts.

ETHICAL CONSIDERATIONS

Figure 4. From Data Collection to Inference: Ethical Risk Layers in XR Biosensing



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As wearable sensors that measure body signals become increasingly integrated into XR systems, many of these ethical considerations extend beyond traditional data privacy concerns. Given the continuous nature of gaze, motion, and physiological capture platforms, they enable both primary recording of behaviors but also secondary inference regarding aspects of users' personal and health information. One previous study (Lake et al., 2024) claims that privacy concerns unique to health care XR include the possibility that "personal and health-related information can be inferred based on VR usage data." Eye-tracking data can constitute sensitive information. Researchers have demonstrated that people can be identified in a VR environment with 96.61% accuracy using less than one minute of passive viewing (Patergianakis & Lambrinoudakis, 2026). Moreover, one study (Cheng & Chukoskie, 2026) states that eye movement patterns and pupil signals can reveal a person's identity and cognitive and affective information. These examples highlight that the issue is not only what XR systems overtly collect but also what they can infer, predict, and re-identify from multimodal biosignals.

These features also raise unique issues around informed consent, user agency, and ethical limits of adaptive personalization. A workshop report on immersive technology from NIST notes that highly personalized immersive experiences can be constructed from emotion states or derived from behavioral and biometric data, but cautions that personalization can lead to manipulation (Fagan & Gilbert, 2025). The report also notes that immersive tech creates tension between data minimization and the data required to fuel immersive experiences, and that user consent, control, and agency may be difficult to achieve if systems can act on involuntary, unconscious, or subconscious behaviors or physical actions (Fagan & Gilbert, 2025). For these reasons, biosensor-rich XR applications may challenge traditional notice-and-consent frameworks as users may not fully understand what is sensed, inferred, or acted upon adaptively in real time.

Further ethical considerations apply when XR biosensing takes place with children, patients, and populations receiving rehabilitation or mental health services. Recent amendments to the U.S. Federal Trade Commission's Children's Online Privacy Protection Act, passed in 2025, expanded the definition of personal information to include biometric data, required parental opt-in consent for certain third-party disclosures (e.g., targeted advertising), and limited the retention of minors' data (*FTC Finalizes Changes to Children's Privacy Rule Limiting Companies' Ability to Monetize Kids' Data*, 2025)2025. However, in practice, declining consent often means being unable to use a service entirely, suggesting that for such protections to be meaningful, the option to decline must be genuine. Recent XR scholarship suggests that eye-tracking and related biosignals in clinical contexts warrant heightened protection because they may enable user re-identification and inference of sensitive personal or health-related attributes (Patergianakis & Lambrinoudakis, 2026). As such, privacy-by-design approaches for biosensor-mediated XR may need to shift away from notice-and-consent frameworks towards strategies that prioritize purpose limitation, data minimization, limited retention, and access controls, with additional caution for vulnerable groups.

CONCLUSION

Wearable sensors that measure body signals and XR are increasingly converging into a shared technological ecosystem with implications that extend well beyond experimental research. Across domains such as sport, rehabilitation, mental health, and training, this convergence is opening new possibilities for real-time monitoring, adaptive feedback, and

more personalized immersive experiences. Yet the importance of this shift lies not only in what these systems can do, but in how responsibly and effectively they can be applied in practice. Ultimately, the future of biosensor-integrated XR will depend on its ability to deliver meaningful value while remaining attentive to usability, governance, and the ethical limits of biometric and behavioral sensing.

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