Comprehensive Analysis of Evolution and Future Trajectory of AR/VR, Establishing Fundamental Requirements Dictated by Human Visual System Such as Field of View, Resolution, And Vergence-Accommodation Conflict

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Abstract:
Augmented Reality (AR) and Virtual Reality (VR) have transitioned from science fiction concepts to tangible technologies with the potential to redefine human-computer interaction. This paper presents a comprehensive analysis of the evolution and future trajectory of AR/VR. We begin by establishing the fundamental requirements dictated by the human visual system—such as field of view, resolution, and vergence-accommodation conflict—and benchmark them against the current state-of-the-art in near-eye displays. Through a scoping review of the field's progression, we analyse publication trends, geographical research focus, and application domains, revealing a maturation phase with strong roots in healthcare, education, and industry. We then delve into the specific optical and display challenges in both VR (e.g., resolution enhancement, VAC mitigation) and AR (e.g., FOV expansion, brightness requirements), drawing on recent advancements in waveguides, microdisplays, and computational optics. Furthermore, we present original findings from a comparative user study on immersive analytics, highlighting that while user performance is comparable in AR and VR, user perception and navigation strategies differ significantly, suggesting a need for context-aware and user-selectable reality modes. Finally, we synthesise these perspectives to outline the future horizons of AR/VR, emphasising the critical role of emerging technologies, such as the AR cloud, cross-virtuality systems, and next-generation micro-LEDs, in driving the next wave of adoption and innovation.

Keywords: Augmented Reality, Virtual Reality, Near-Eye Displays, Human Visual System, Immersive Analytics, Optical Combiners, Microdisplays, Vergence-Accommodation Conflict.

1. Introduction

As one of the most promising candidates for next-generation mobile platforms, Augmented Reality (AR) and Virtual Reality (VR) have the potential to revolutionise the ways we perceive and interact with various digital information [1]. From the bulky cathode ray tube to compact flat panels, display technologies have evolved rapidly. The next generation is no longer limited to screens placed in front of users but aims to revolutionise interactions between users and their surrounding environment [2]. At one end of the spectrum is VR, which blocks the entire ambient environment to offer an immersive virtual world. At the other end is AR, which enriches the real world by overlaying digital content, pursuing high-quality see-through performance [1].

These technologies are part of the "virtuality continuum" defined by Milgram and Kishino, a spectrum that ranges from the completely real to the completely virtual, with Mixed Reality (MR) encompassing the space between [3]. The ideal goal of AR and VR development is to offer reality-like, crystal-clear images that can simulate, merge into, or rebuild the surrounding environment while avoiding user discomfort. However, this remains challenging, especially for AR systems, as most components demand further performance enhancement and miniaturisation [1].

The popularity of AR and VR has fluctuated over the years. While initially a focus of intense research and hype, these technologies have experienced periods of disillusionment. However, recent technological improvements in devices and processing hardware are fueling a resurgence, moving them from laboratories into consumer hands and specialised industrial applications [4]. This paper aims to provide a holistic perspective on this journey. We analyse the evolution of

AR/VR, benchmark current capabilities against the ultimate limits of human vision, detail the technical challenges and potential solutions, and forecast future trends that will shape the next decade of immersive technology.

2. Methodology and Analysis of Research Evolution

To understand the trajectory of AR and VR, a scoping review of the field's research landscape was conducted, analysing publication trends, geographical contributions, and primary application domains.

2.1 Publication Trends and the Hype Cycle

An analysis of publication volume from the year 2000 reveals a significant peak in both AR and VR research around 2017-2018, followed by a notable decline (Table 1, Figure 1). This pattern aligns with the Gartner Hype Cycle, a model that estimates the maturity and adoption of emerging technologies [5].

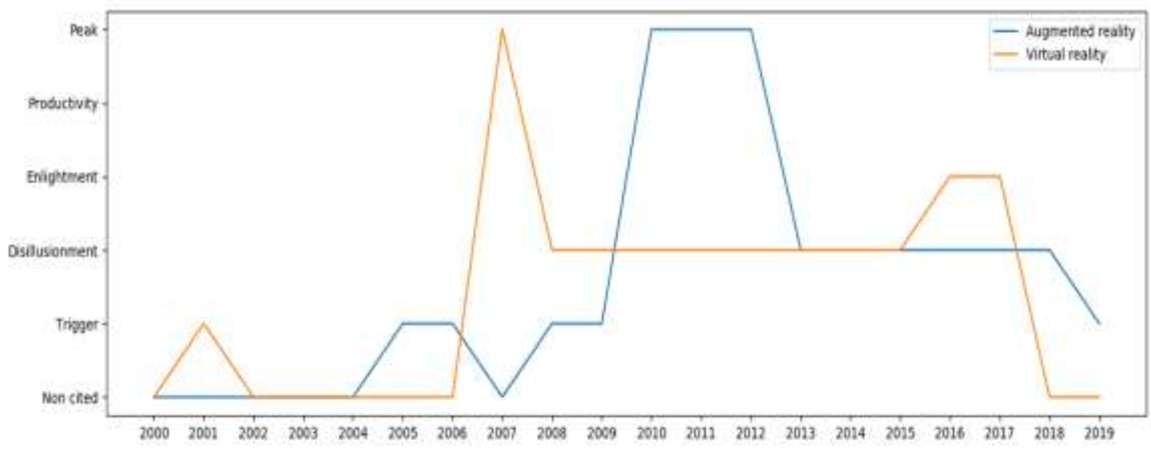
Table 1: Publication Evolution (Selected Years)

Year	AR Number of Publications	Variation	VR Number of Publications	Variation
2000	2300	-	14,100	-
2001	2570	11.74	15,900	12.77
2002	3190	24.12	17,800	11.94
2003	5540	73.67	19,800	11.24
2004	4640	−16.25	23,200	17.17
2005	5160	11.20	24,600	6.03
2006	5820	12.80	29,100	18.29
2007	6670	14.60	29,900	2.75
2008	7410	11.09	34,000	13.71
2009	8070	8.91	36,500	7.35
2010	10,800	33.83	38,600	5.75
2011	13,400	24.07	40,200	4.14
2012	16,900	26.12	42,100	4.73
2013	19,700	16.57	45,700	8.55
2014	24,400	23.86	45,900	0.44
2015	27,600	13.12	46,100	0.44
2016	30,500	10.51	50,700	9.98
2017	35,400	16.06	57,400	13.21
2018	31,100	−12.05	47,600	−17.07
2019	2570	−79.92	27,700	−41.81

AR first appeared on the Hype Cycle in 2005, reaching its "Peak of Inflated Expectations" around 2010 and entering the "Trough of Disillusionment" from 2013 to 2018. In 2019, it re-emerged as "AR Cloud," indicating a new wave of interest driven by cloud computing. VR followed a similar path, appearing as "Virtual Worlds" at its peak in 2007 and transitioning through the trough before reaching the "Slope of Enlightenment" around 2016. Its recent disappearance from the cycle suggests it is entering a "Plateau of Productivity" [4]. This indicates that while the initial frenzy has subsided, the technologies are maturing and finding stable, productive applications.

Figure 1: Evolution of Publications.

(A graphical representation of the data in Table 1, showing the peak in 2017-2018 and subsequent decline.)



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2.2 Geographical and Topical Focus

An analysis of 163 selected research papers reveals that the European Union (EU) and the United States (USA) are the dominant forces in AR/VR research, accounting for over 60% of publications (Figure 2). The most prevalent research topics are Research & Development (R&D), Healthcare, Education, and Industry.

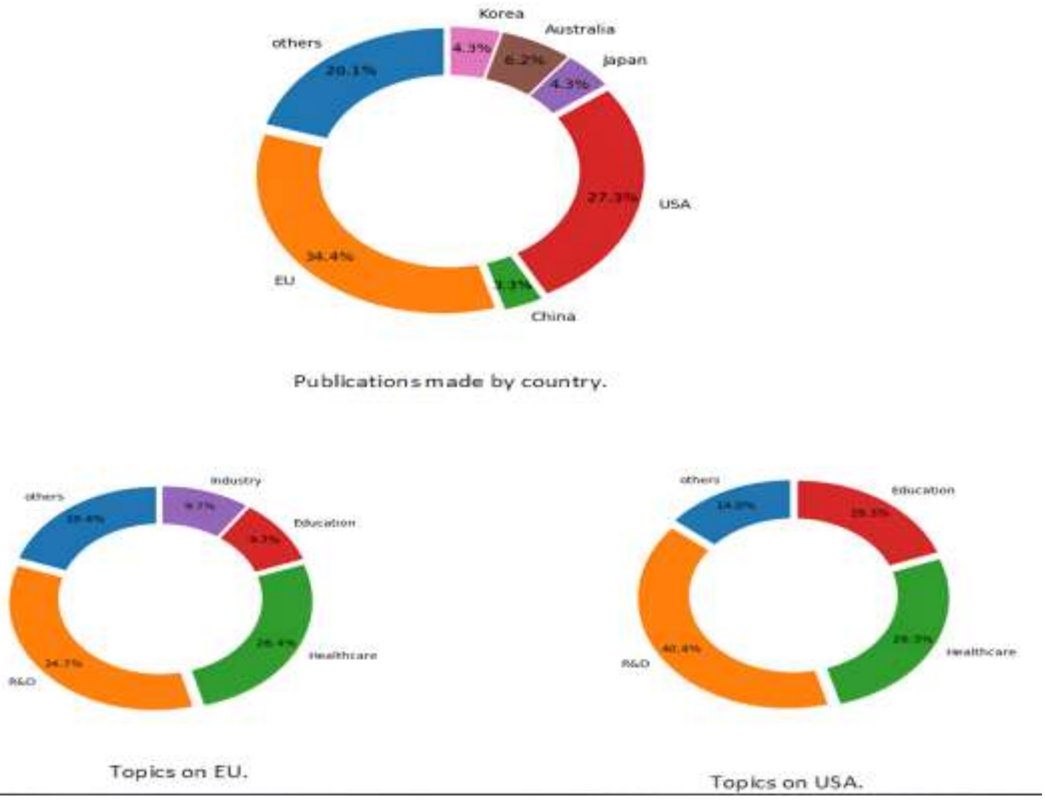


Figure 2: Research Focus by Region and Topic.
(Pie charts showing: 1) EU and USA as the top publishing regions; 2) The distribution of research topics in the EU, led by Healthcare and R&D; 3) The distribution in the USA, similarly led by Healthcare and R&D.)

Healthcare: This is the most prominent application field. The primary specialisations are surgery (e.g., simulation, planning, and assistance), psychology (e.g., phobia treatment), and rehabilitation (e.g., post-stroke therapy) [4, 6].

Education: Applications are focused on middle school and university levels, with tools for teaching mathematics, sciences, anatomy, and languages through interactive, immersive experiences [7].

Industry: The main applications are maintenance (e.g., guided procedures), productivity enhancement (e.g., collaborative design), and worker training [8].

This analysis confirms that AR and VR have moved beyond pure research and are delivering tangible value in critical sectors.

3. The Human Visual System: The Ultimate Benchmark

The development of high-quality AR/VR displays is fundamentally constrained by the capabilities of the human visual system (HVS). Key parameters include field of view, angular resolution, dynamic range, and depth cues.

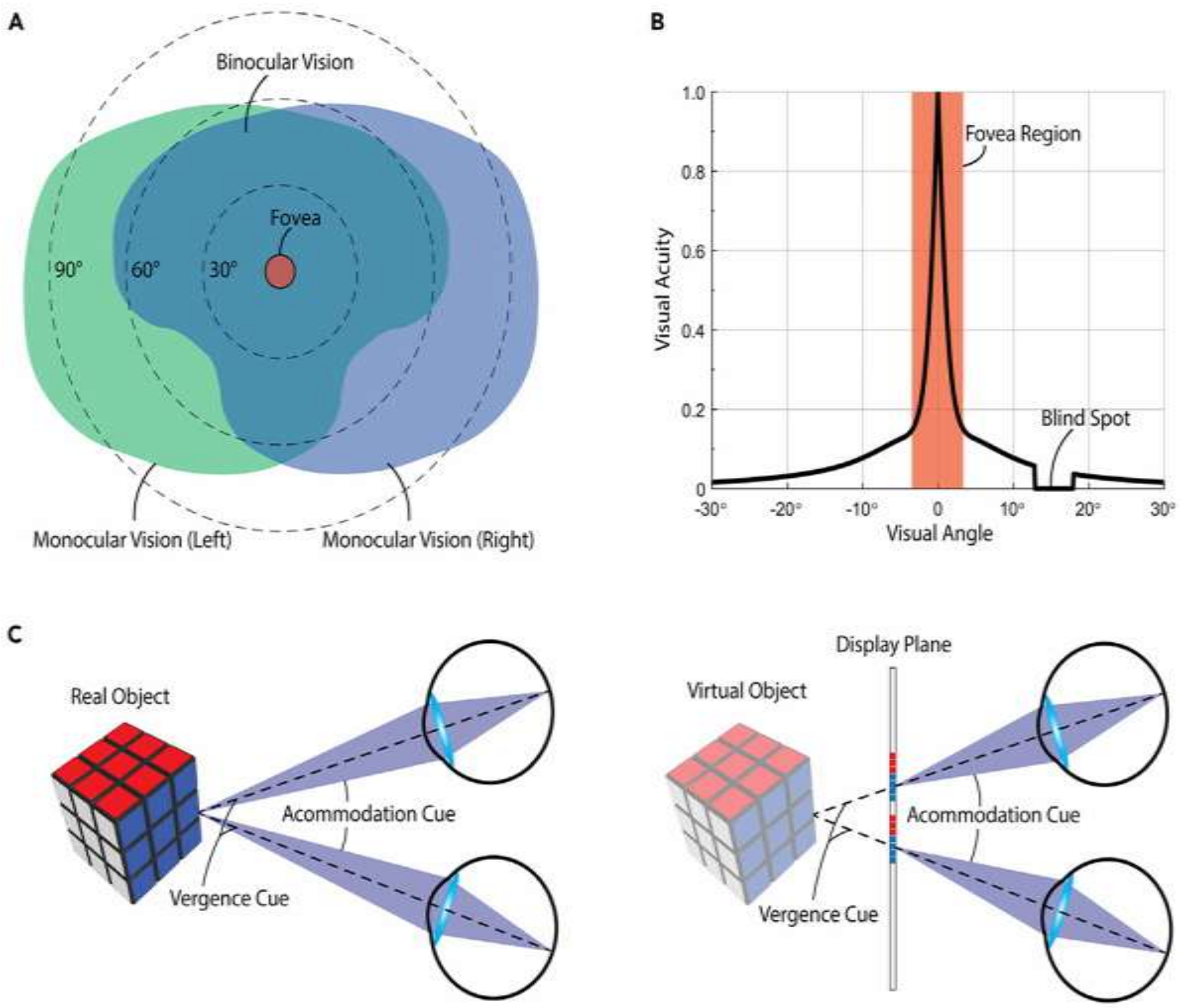
3.1 Field of View (FOV) and Resolution

The human binocular FOV is approximately 200° (horizontal) by 130° (vertical). The resolution limit is determined by the cone density in the fovea, corresponding to a visual acuity of about 0.5 arcminutes, or 120 pixels per degree (ppd) for 20/10 vision [1, 9]. There is a direct trade-off between FOV and resolution density for a fixed number of display pixels.

For VR: Achieving a wide FOV that matches human vision is relatively straightforward optically, but it often results in a low ppd, causing the "screen-door effect." To achieve a 100° FOV with 60 ppd (20/20 vision), a display with 6K horizontal resolution is required—a significant challenge in terms of cost, data rate, and power [1].

For AR: The primary challenge is achieving a decent FOV in the first place. Most current AR waveguides offer a diagonal FOV of around 50°, far from the human limit of ~200° diagonal [1].

Figure 3: Performance of Human Vision.
((A) The profile of human FOV.
(B) The relation between visual acuity and visual angle.
(C) Sketch of the Vergence-Accommodation Conflict (VAC).)



3.2 Vergence-Accommodation Conflict (VAC)

A significant source of visual fatigue in 3D displays is the VAC (Figure 3C). In the real world, the vergence (rotation of the eyes) and accommodation (focusing of the lenses) cues are linked. In most current VR and AR displays, images are presented on a single fixed plane. The eyes must accommodate to that plane while verging to different depths to perceive stereoscopy, causing a conflict that leads to discomfort and distorted depth perception [1, 10].

3.3 Brightness and Contrast

The human eye is a high-dynamic-range system. For AR displays, which must compete with ambient light, brightness is a critical parameter. The Ambient Contrast Ratio (ACR) is a key metric [1]:

$$ACR = \frac{L_{\text{on}} + L_{\text{ambient}} \cdot T}{L_{\text{off}} + L_{\text{ambient}} \cdot T}$$

Where Lon/off is the display luminance and T is the transmittance. For outdoor use (e.g., 10,000 lux), an ACR of 5:1 for adequate readability may require over 10,000 nits of display brightness. Current state-of-the-art AR systems typically support only up to 500–2,500 nits, limiting them to indoor use [1].

4. Virtual Reality: Pushing the Boundaries of Immersion

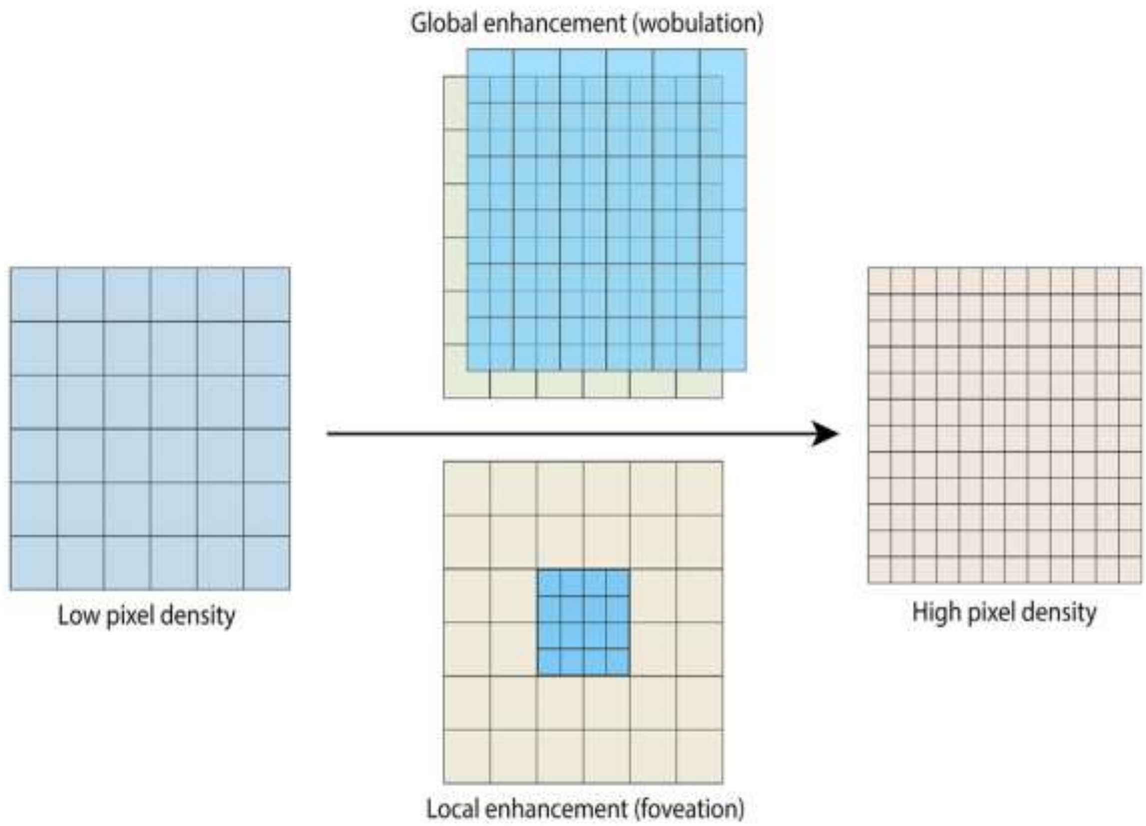
4.1 Enhancing Resolution

Beyond simply increasing panel resolution, two promising approaches are:

Global Enhancement (Wobulation): This technique uses mechanical or optical shifting (e.g., with liquid crystal deflectors) to double the apparent pixel density through temporal multiplexing, reducing the screen-door effect without changing the native panel resolution [1, 11].

Local Enhancement (Foveated Rendering): This approach exploits the non-uniform resolution of the HVS, rendering the foveal region at high resolution and the periphery at lower resolution. This can be achieved with multi-panel systems or using a transparent projection screen over a main display [1, 12].

Figure 4: The Development Trend of Panel Resolution.



4.2 Advanced Viewing Optics
The optical lens is critical for image quality and form factor.

Fresnel Lenses: Prevalent in commercial VR for their compactness and weight, but suffer from diffractive artefacts and stray light.

Pancake Lenses: Use folded optics with reflective surfaces to create a much shorter focal length, enabling more compact headsets. The trade-off is a significant loss in light efficiency (~75%) and demanding polarisation control [1].

Emerging Flat Optics: Metalenses and Pancharatnam-Berry phase lenses based on liquid crystals or metasurfaces offer ultra-thin profiles for aberration control and system miniaturisation [1, 13].

4.3 Addressing the Vergence-Accommodation Conflict
Several methods are being explored to mitigate VAC:

Varifocal Displays: Use eye-tracking to determine the user's gaze depth and shift the display focal plane accordingly using adaptive optics [1].

Multifocal Displays: Simultaneously present images on multiple discrete focal planes, providing more accurate accommodation cues. The density of planes can be balanced against system bandwidth [1, 14].

Holographic and Light Field Displays: These aim to reconstruct the true wavefront or geometric rays of a 3D scene, providing correct retinal blur. However, they currently face challenges with limited FOV, resolution, and computational load [1].

5. Augmented Reality: The Challenge of Seamless Integration
5.1 Expanding the Field of View
The FOV in AR is often limited by the physics of the optical combiner, especially in lightguide-based systems.

High-Index Materials: The FOV in a lightguide is limited by the critical angle for Total Internal Reflection (TIR). Using high-refractive-index glass ($n_d \geq 1.9$) reduces the critical angle, allowing a wider range of light angles to propagate, thereby increasing the FOV [1].

Multiplexing: Techniques like spatial and polarisation multiplexing can combine multiple images to create a larger effective FOV. For instance, polarisation volume gratings (PVGs) can be designed to diffract left- and right-circularly polarised light at different angles, effectively doubling the FOV [1, 15].

Maxwellian View: This method forms an image of the light source on the viewer's pupil, making the image focus-free and tolerant to the eye's accommodation. While it solves VAC, it traditionally has a very small "eyebox." Recent work combining the Maxwellian view with holographic optical elements (HOEs) and pupil expansion has demonstrated large FOVs (e.g., 100° diagonal) [1, 16].

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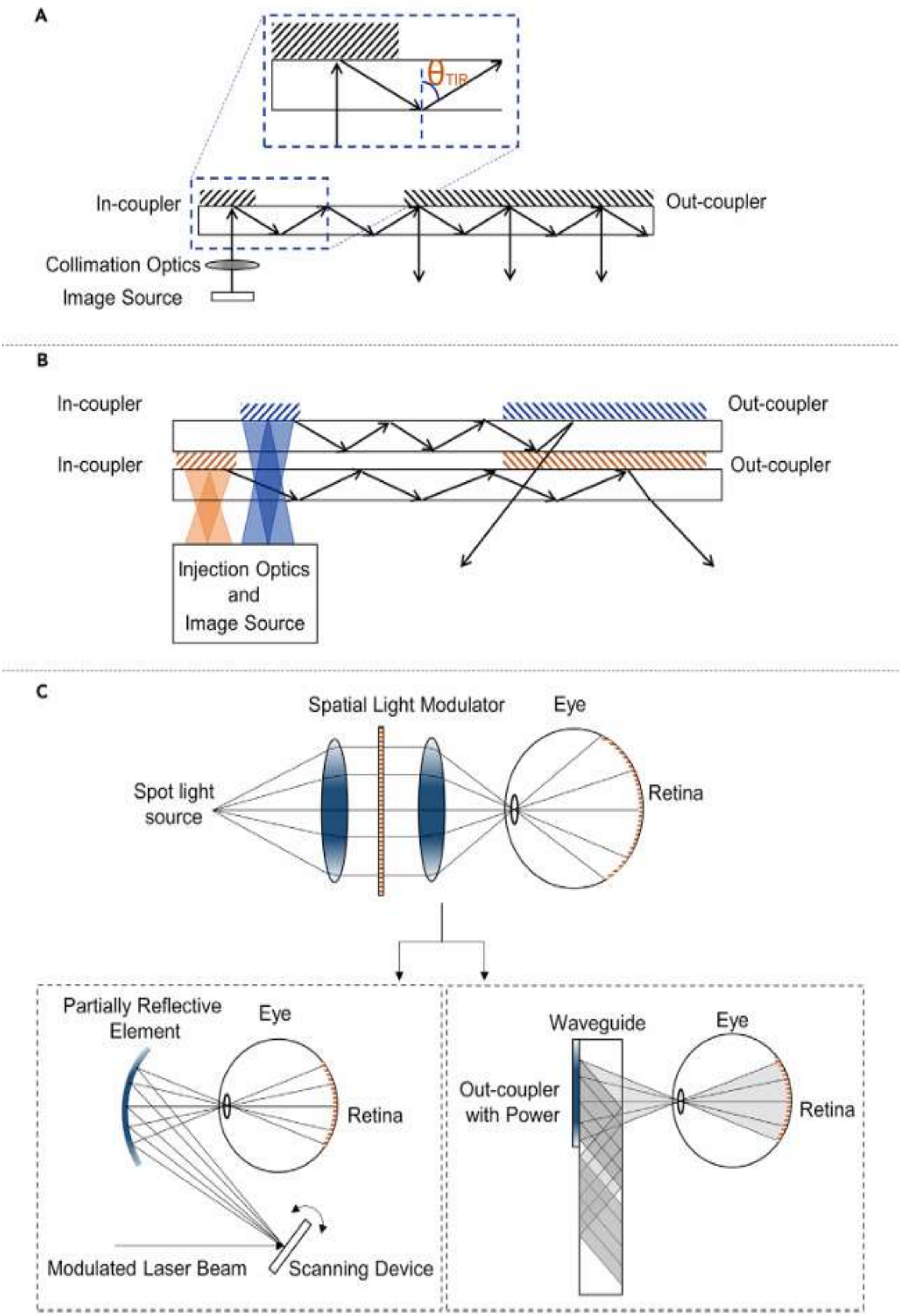
Figure 5: Optical Structures of AR Systems with Extended FOV.



5.2 Display Engines and Combiners: A Roadmap

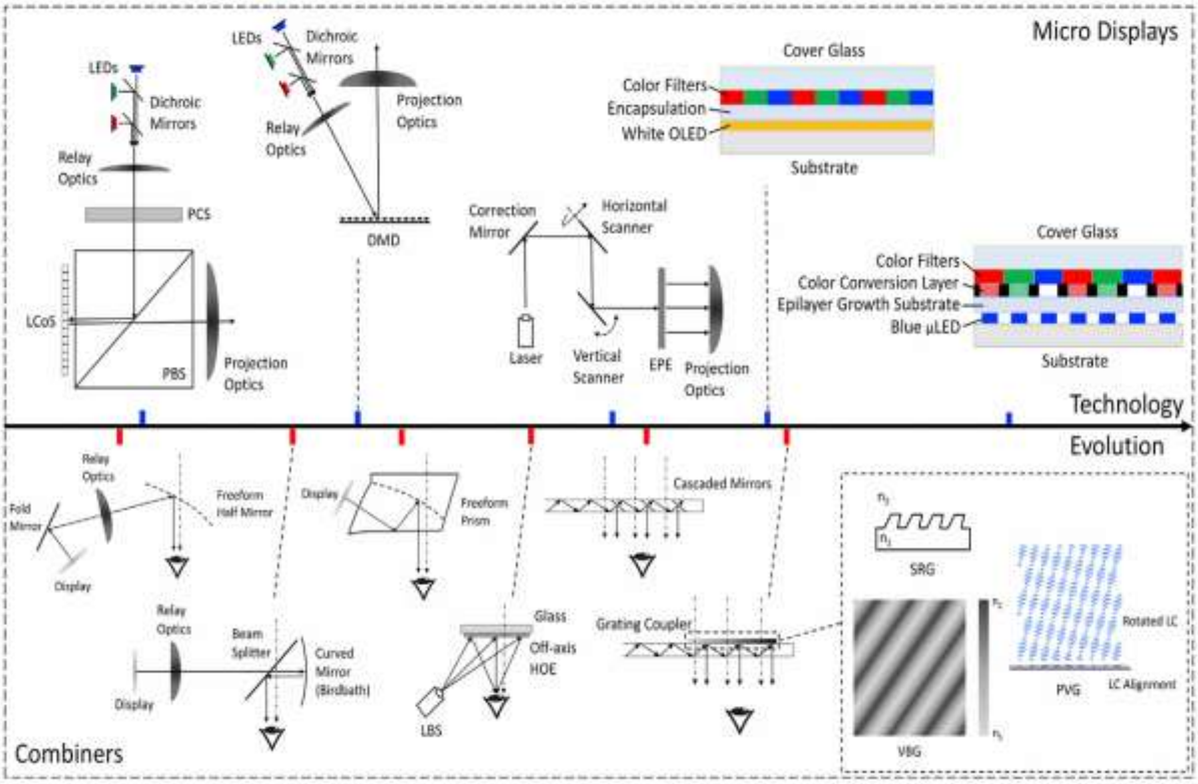
Achieving high brightness and efficiency requires advancements in both the microdisplay and the combiner optics.

Table 2: Comparison among AR Display Light Engines

Display	Maturity	Brightness (Nits)	Light Efficiency	Form Factor	Optical System Complexity	Contrast Ratio
LCoS	High	10^4–10^5	Low	Large	Medium	~10^3:1
DLP	High	10^4–10^5	Medium	Medium	Medium	~10^3:1
µOLED	Medium	10^3–10^4	High	Small	Low	~10^4:1
µLED	Low	10^5–10^6	High	Small	Low	~10^5:1
LBS	Medium	>10^4	High	Small	High	~10^5:1

Micro-LED (µLED) is the most promising future technology, offering exceptional brightness, efficiency, and contrast. However, it faces major challenges in mass transfer and full-colour implementation for ultra-small pixel pitches (<5 µm) [1]. Combiners can be reflective (e.g., birdbath, freeform prism) or diffractive (e.g., Surface Relief Gratings (SRG), Volume Bragg Gratings (VBG), PVG). Diffractive combiners in waveguides enable a slim form factor but often at the cost of efficiency, colour uniformity, and eye-box size, requiring sophisticated 2D exit pupil expander designs [1].

Figure 6: Schematic Plots of Major Microdisplays and Combiners.



6. User-Centric Analysis: A Comparative Study in Immersive Analytics

Beyond hardware, understanding user interaction is crucial. A comparative study was conducted to evaluate user performance and perception in AR vs. VR for immersive analytics tasks using 3D scatter plots [17].

6.1 Study Design

A within-subjects design was used with 40 participants. They performed identical data analysis tasks (e.g., outlier detection, cluster recognition) in both AR and VR using a Varjo XR-3 headset to control for hardware variables. Metrics included task completion time, accuracy, NASA-TLX (workload), Presence Questionnaire, and System Usability Scale (SUS).

6.2 Key Findings

Performance: No significant difference was found in task accuracy or completion time between AR and VR, refuting the hypothesis that performance would be higher in one environment over the other.

Workload and Frustration: While overall workload was similar, frustration in VR was less correlated with other workload aspects (like mental demand and effort) than in AR (Figure 7). This suggests users have a higher tolerance for cognitive load and potential errors in VR, possibly due to a more immersive "flow" state.

Navigation and Posture: Contrary to the hypothesis that users would move more in AR, participants exhibited more varied postures and a greater incidence of walking in VR (Figure 8). This indicates that a well-set-up VR environment can make users feel secure enough to engage in full-body navigation.

User Perception: Qualitative feedback revealed a strong preference for AR's situational awareness and safety ("AR is really cool. You safely see everything around you"), while some found VR's full immersion led to deeper focus, with several users noting they "did not notice" the shift between environments once engaged with the task.

Figure 7: Correlation Between Categories in NASA TLX.

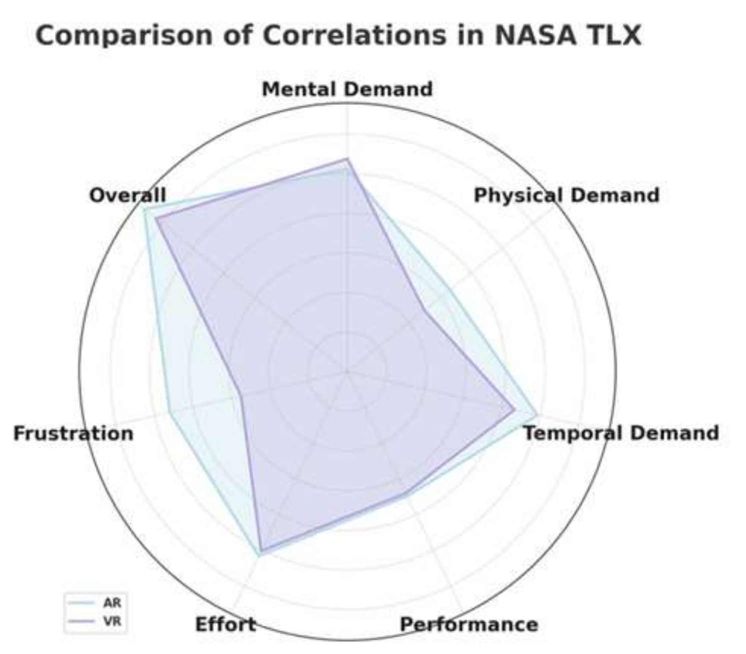
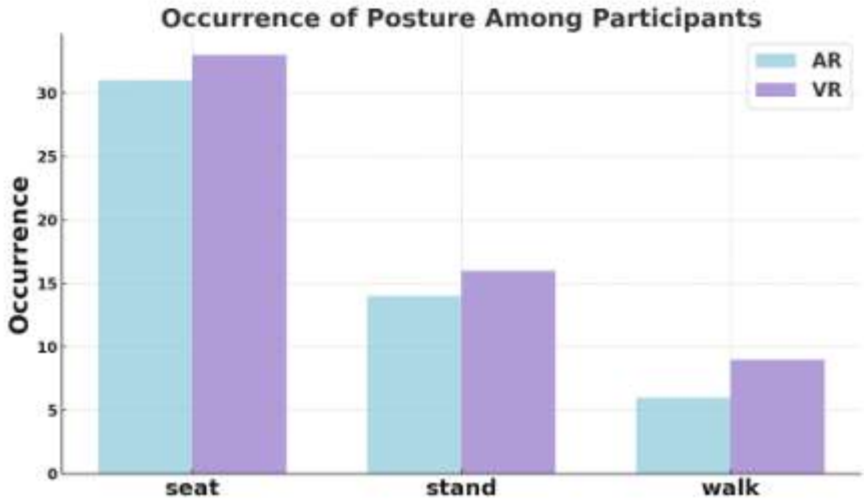


Figure 8: Postures in the Experiment.



6.3 Implications for Design

This study underscores that the choice between AR and VR is not about raw performance but about user experience and context. For tasks requiring deep, uninterrupted focus and where physical navigation within the data is beneficial, VR may be preferable. For tasks where users need to frequently reference the real world, use physical tools, or maintain situational awareness, AR is the superior choice. The ideal future system is not AR or VR, but a cross-virtuality platform that allows users to fluidly transition between states based on their immediate needs.

7. The Road Ahead: Synthesis and Future Horizons

The evolution of AR and VR is a story of converging advancements. Our analysis shows a field that has weathered its hype cycle and is now building a foundation of real-world utility. The future will be shaped by the resolution of key technical challenges and the emergence of new paradigms.

7.1 Near-Term Horizons (2-5 Years)

Micro-LED Commercialisation: The successful mass production of full-colour µLED microdisplays will be a watershed moment, particularly for AR, finally delivering the brightness needed for outdoor use in a compact form factor.

Advanced VAC Mitigation: Varifocal and multifocal displays will move from research prototypes into high-end consumer and professional products, significantly improving comfort and enabling longer usage sessions.

The Rise of the AR Cloud: Cloud-based spatial computing platforms will enable persistent digital content anchored to the real world, facilitating shared multi-user experiences and offloading complex processing from the device.

7.2 Long-Term Visions (5-10 Years)

Ubiquitous Cross-Virtuality: The distinction between AR and VR will blur. Users will seamlessly transition from a fully immersive VR workspace to an AR-enhanced view of their physical office, with data and context preserved between states.

Neuromorphic Interfaces: Displays will move beyond simply presenting images to directly interfacing with the human visual system, potentially using techniques like holography to perfectly match the eye's optics and eliminate conflicts.

Context-Aware and Proactive Systems: AR/VR devices will evolve into intelligent assistants that understand user intent, proactively surfacing relevant information and adapting the interface in real-time based on biometric, environmental, and task data.

8. Conclusion

The journey of AR and VR from conceptual marvels to practical tools is a testament to sustained innovation. While the path has been marked by periods of inflated expectations and subsequent disillusionment, the technologies have emerged stronger and more focused. Today, they are delivering tangible value in critical sectors like medicine, education, and industry. The fundamental challenges of matching the human visual system—achieving wide field-of-view, high resolution, comfortable depth cues, and sufficient brightness—are being systematically addressed through breakthroughs in optics, materials, and computational imaging.

Crucially, we are learning that the value of these technologies is not solely in their technical specifications, but in their ability to adapt to human needs. As the user study showed, the choice between AR and VR is contextual and personal. The future of immersive computing, therefore, lies not in a single, dominant reality, but in a fluid spectrum of experiences. By continuing to push the boundaries of what is possible while remaining grounded in human-centric design, AR and VR are poised to transition from specialised tools to universal interfaces, fundamentally expanding human perception and capability in the decades to come.

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