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Research Article

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The global classroom: vision-driven XR across the time-space matrix

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Abstract: This article proposes a vision-driven roadmap for Extended Reality (XR) in education that treats technology as infrastructure rather than spectacle. Two anchors guide the work. First, *vision-led design* focuses on persistent educational needs before tools. Second, the *long path to adoption* reminds us that mainstream impact follows decades of refinement. We adapt and apply the Computer Supported Cooperative Work (CSCW) time-space matrix to the educational context, using Germany as a case study to map current practices. The map reveals a strong bias toward same-time, same-place activities, limited use of asynchronous and distributed work, and integration barriers, including novelty effects, preparation time, infrastructure, and interoperability. We then outline development pathways across three horizons. In 10–15 years, co-located lessons mature through teacher-editable, persistent scenes and modular "nuggets" that reduce preparation cost. In 25–35 years, hybrid integration connects sites at scale, with shared environments that support both live collaboration and asynchronous work with Artificial Intelligence (AI) peers. At 50 years, balanced use of all four quadrants becomes routine, supported by safer interfaces, richer haptics, and portable AI companions that respect privacy. Throughout, we argue that XR should be judged by how well it fosters modelling and simulation literacy, collaboration across time and place, AI literacy, and embodied making, all while safely offloading teachers' routine tasks such as basic explanations, first-pass grading, and basic task sequencing.

Keywords: extended reality; collaborative learning; global classroom; vision-driven innovation; persistent environments; AI companions

1 Introduction

It is a school day in 2075. In Bremen, Germany, a biology class activates their lightweight mixed-reality headsets and steps into a shared rainforest that overlays their classroom. Unlike today's transient Virtual Reality (VR) experiences, this environment persists: yesterday's soil samples remain where students placed them, measurement data hovers beside marked trees, and footprints show where previous groups explored. When a partner school in Sejong, South Korea, joins the next day, they find the Bremen students' spatial notes and observations waiting for them. For these students, this is not remote learning. It is simply how school works when collaboration is no longer constrained by time or place.

The point of this article is not to predict gadgets. We begin with human needs and constraints, then ask which problems in schooling are worth solving and whether Extended Reality (XR) is a suitable means to address them. Only under those conditions is it reasonable to treat XR as potential infrastructure rather than a short-lived novelty. This argument rests on two conceptual anchors, each offering a distinct lens on XR's role in education. The initial anchor is provided by Hiroshi Ishii's vision-driven approach, which begins by identifying the enduring issue and only then proceeds to designing a tool to resolve it.[1,2] Ishii leads MIT's Tangible Media Group, and his vision-driven work from Tangible Bits to Radical Atoms is widely regarded in Human-Computer Interaction (HCI) and design, shaping decades of interaction research and practice.

In schools, the constraints are familiar:

- Time is divided into short lessons
- Space is fixed to a room

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- Teaching expertise and specialist knowledge are scarce and unevenly distributed
- Assessment still rewards individual recall more than collaborative sense-making
- Continuity and collaboration over time and space is limited

For schools, XR will only matter in the long run if it helps loosen these constraints.

Bill Buxton's "long nose of innovation" is the second anchor.[3] Technologies that look sudden to the public often spend decades in quiet refinement. Buxton articulated this argument in his design writing and is widely recognised as a pioneer in human-computer interaction; his book *Sketching User Experiences* is a standard reference in design education and practice.[4] If XR is to be part of everyday schooling within 25–50 years, the groundwork must be laid now. That work is not a shopping list of headsets or tablets. It is an ecosystem of adaptable simulations, multi-user platforms, and teacher-first tools that survive software updates and reduce preparation time rather than add to it.

We ground the empirical picture in Germany while drawing on international pilots. Although Germany is our anchor case, the constraints we target and the collaboration patterns we map recur across many Organisation for Economic Co-operation and Development (OECD) systems, so the framework and development pathways are intended to generalise with local adaptation. Using an adapted time-space matrix, we map where collaboration happens and where it stalls, before reviewing present digital practice. We then outline development pathways across three horizons: foundation building in the next decade, hybrid integration at 25–35 years, and a cautious 50-year view in which global learning spaces, richer haptics and Artificial Intelligence (AI) companions are plausible if governed well. When we refer to AI companions, we distinguish short-term, account-bound agents used within a learning environment from longer-term, portable companions that span institutions and years. The question is simple: how can vision-driven XR address fundamental challenges in schooling so that technology serves the goals of education, rather than forcing education to adapt to the limitations of current devices? We set the frame, map the present, outline three horizons and end with the challenges and governance needed to ensure XR in education remains problem-driven and human-centred.

2 Framework: vision-driven innovation and the long path to adoption

2.1 Vision-driven innovation

The key distinction between vision-driven and technology-driven innovation lies in their starting point. A technology-driven approach begins with a product, then searches for problems it might solve. This often yields short-lived solutions: devices become obsolete as user needs evolve, and software outpaces hardware; even widely adopted standards endure only for a time. Vision-driven innovation, by contrast, focuses on an enduring human need or process rather than any specific technology. Consider music: formats have shifted from vinyl and cassette to CD, DVD, and streaming, not because technology itself was the goal, but because listeners sought greater accessibility, convenience, and variety. The medium changes; the core desire persists.

In practice, the always sought-after "killer app" for any vision must address a "killer problem". If the underlying need is weak or ill-defined, sophistication will not translate into lasting impact. Applied to education, this means starting with the constraints outlined above and asking how existing or emerging tools might loosen them: fragmented time, fixed space, scarce expertise,[5,6] recall-focused assessment, and limited continuity. From there, one can explore how existing or emerging tools can be adapted or developed to address these issues. As Alan Kay put it, "The best way to predict the future is to invent it".[7] Directing research toward genuine, high-impact problems shapes the conditions for future solutions to succeed when supporting technologies mature. From a media-didactics perspective, XR should address a concrete educational aim and offer meaningful learner activities rather than focus on technology features like "immersion".[8]

Critiques of vision-led approaches are important. Visions can amplify designer bias and confirm preconceptions instead of reflecting user priorities.[9] They can also crystallise into illegitimate targets that steer present design toward self-fulfilling prophecies.[10] Given the complexity of classrooms and the uncertainty of technological change, converging on any bias-free vision is difficult. Weiser's well-known Sal scenario illustrates the risk, since many of its specifics did not materialise as imagined, which led Bell and Dourish to call it "yesterday's vision of the future" and to warn about misplaced design effort.[11,12] To mitigate these risks, we treat visions as hypotheses open to critique and revision, and we advocate participatory envisioning that seeks social legitimation from prospective users. Similar approaches have proven effective in the past. For example, the "contravision" technique, which presents contrasting utopian and dystopian scenarios to the public, was shown to help invite debate that shapes a more balanced and realistic middle ground.[13]

Ishii distinguishes three layers that move at different speeds: fast-changing technologies, decade-scale applications and long-lived visions (cf. Figure 1). For education, the middle layer is the leverage point. Visions are too abstract to timetable or assess; devices turn over faster than curricula and procurement cycles. Middle-layer applications define stable workflows, data models and assessment hooks that survive device churn. For example, a VR headset is a current technology; the application could be shared spatial learning in a persistent room,[14] but the vision behind it is to remove time and place as barriers to understanding.

Because the middle layer connects design intentions with classroom realities, iterative validation is essential. Design-based research offers a suitable methodology for this context, embedding technology development in authentic educational settings and cycling between design and evaluation to generate both practical artefacts and theoretical insight.[15,16] The pathways outlined in Section 4 are conceived as candidates for such iterative refinement rather than as finished prescriptions.

2.2 The long nose of innovation

It is easy to overlook how long it takes for new technologies to reach routine classroom use. The visible "wow" moment is usually the tip of a long period of refinement. Following Buxton's *long nose of innovation*,[3] we treat this as a planning heuristic rather than a fixed timeline. What tips systems into the mainstream is a mature ecosystem, not a single breakthrough. Our 10, 25, and 50 year horizons are planning lenses, not predictions of invention dates.

The long nose is visible in recent AI developments. Large Language Models (LLMs) felt sudden in 2022, yet their technical roots trace to the 1960s and 1990s and include attention mechanisms[17] and generative pre-training steps between 2018 and 2020.[18–20] VR and Augmented Reality (AR) have an even longer arc. Sutherland's 1960s head-mounted display sketched a "looking glass into a mathematical wonderland".[21] Mobile AR still constrains the field of view to a small window,[22] and early smart glasses stalled on weak use cases and privacy concerns.[23] Surveys of AR document steady, multi-year convergence across tracking, displays, and interaction.[24,25] For XR in education, we therefore argue for a credible progression from lab prototypes to classroom-ready tools that target genuine school problems.

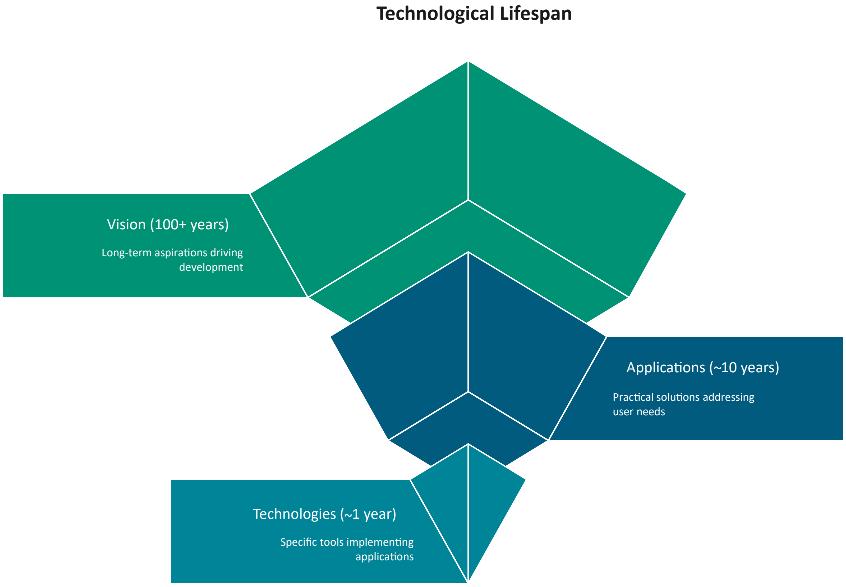

Figure 1: Ishii's model of layered change: fast-changing technology, decade-scale applications, long-lived visions. For XR in education, the middle layer (applications) is the leverage point: durable workflows and data models that survive device turnover while serving persistent human needs.

2.3 The time-space matrix for schooling

Robert Johansen's time-space matrix for Computer Supported Cooperative Work (CSCW) classifies collaboration along two axes: time (same time versus different time) and place (same place versus different place).

The result is four quadrants:

- same time/same place (in-person, real-time interaction, ST/SP)
- same time/different place (remote, real-time collaboration, ST/DP)
- different time/same place (a shared space used at different times, DT/SP)
- different time/different place (asynchronous work from separate locations, DT/DP)

Developed for workplace collaboration, the matrix also adapts well to educational settings. It helps identify which modes are currently used, which are underutilised, and where XR might open new possibilities. In this article, it also serves as a reference for mapping the present state of German schools and for envisioning future developments.

The time–space matrix is a useful lens, yet it can be misleading if read too literally. Work in CSCW shows that temporal and spatial categories blur in practice: collaboration depends on social and organizational factors, not just time/place coordinates.[26] Media labelled as *asynchronous* are routinely used synchronously: for example, email is (or was) often treated as near–real-time chat and also used for task management.[27] Learners in the same room may also prefer to coordinate through a shared document rather than talk, illustrating that *place* is socially constructed, not only physical.[26,28] For this article, we therefore treat the quadrants as use-modes that participants move between during an activity, rather than as device categories. This stance aligns with theories that emphasise matching media capabilities to tasks and with media ecologies where people fluidly switch among channels.[29] Sessions can traverse the diagonals. For example, a DT/DP investigation turns into ST/DP when a partner class joins live, or briefly becomes ST/SP when students gather around a table. Figure 2 should be read with that fluidity in mind.

Figure 2 maps this framework onto school education. Traditional classroom learning sits mainly in ST/SP; video conferencing offers basic ST/DP; learning management systems (LMS) provide rudimentary DT/DP. None matches the richness of spatial, persistent XR.

Each quadrant also foregrounds different learning objectives and didactic strategies. ST/SP supports direct instruction, guided experimentation, and the social negotiation central to collaborative learning;[30] its strength is immediate feedback and co-regulation among peers. ST/DP extends these collaborative dynamics across sites, foregrounding intercultural competence, perspective-taking, and the ability to coordinate shared artefacts in real time. DT/SP shifts the emphasis toward continuity and iterative refinement: learners revisit and build on prior work in a shared physical or virtual space, practising self-regulated learning and long-term project management. DT/DP demands the highest learner autonomy, supporting asynchronous co-creation in persistent environments where spatial annotations, AI peer contributions, and versioned scene states accumulate over time and across sites. Recognising which objectives align naturally with which quadrant helps teachers choose the right mode for a given task rather than defaulting to ST/SP out of habit.

2.4 Why is XR useful for educational challenges?

The constraints outlined above (fragmented time, fixed space, scarce expertise, and limited continuity) are not new, and many have been partially addressed by existing technologies. Video conferencing connects distant learners, cloud documents enable asynchronous collaboration, and learning management systems track progress. Why, then, does XR warrant consideration as educational infrastructure rather than simply another digital tool?

Three interconnected affordances distinguish XR from conventional technologies and position it to address educational needs in ways that existing tools cannot fully replicate. First, XR supports embodied spatial understanding in ways that flat screens and text cannot. Abstract concepts in physics, chemistry, geometry, and biology often resist comprehension through diagrams alone. When learners manipulate 3D models at scale, observe dynamic processes from multiple perspectives, and develop intuition through physical interaction, they engage what cognitive science calls embodied cognition: the tight coupling between physical action and conceptual understanding.[31,32] Unlike desktop simulations that present phenomena through a window, XR situates the learner inside the system itself, supporting spatial reasoning and intuitive grasp of complex relationships.[33] This immersive quality is not merely a technical feature but a psychological experience: learners develop a sense of presence that transforms how they engage with spatial information.[34]

This spatial quality extends to collaboration in distinctive ways. While desktop 3D viewers can display spatial annotations, XR supports embodied navigation through shared environments. When a biology group annotates a virtual cell in XR, a partner class visiting days later doesn't

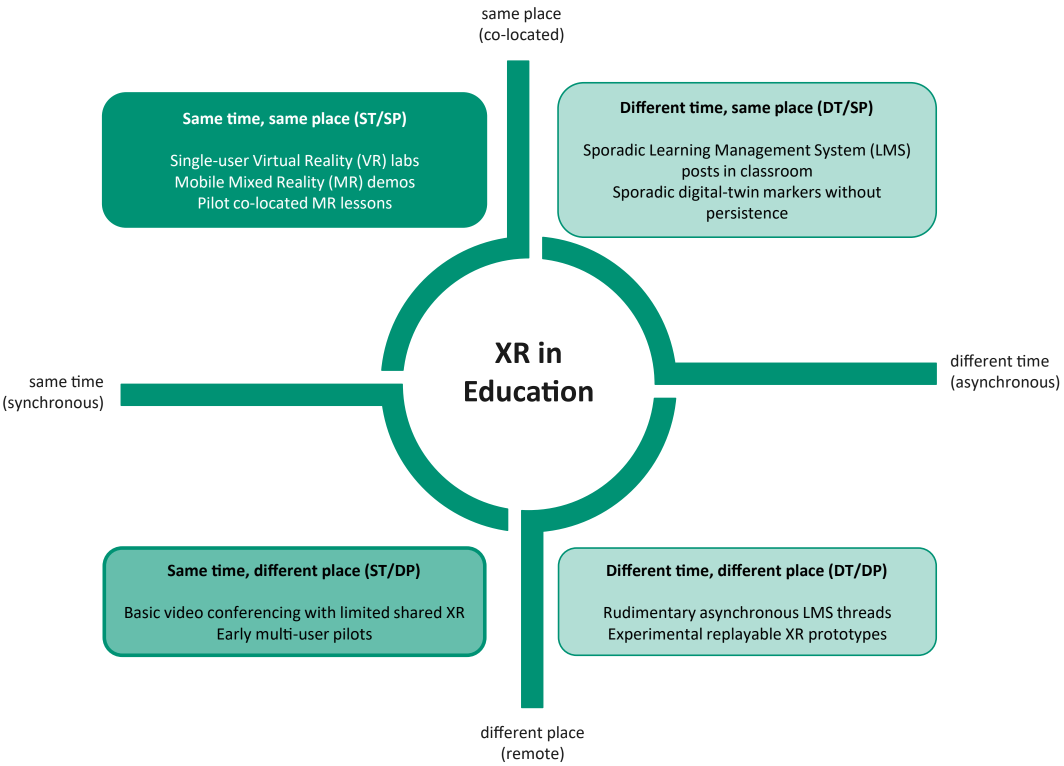

Figure 2: Computer supported cooperative work matrix adapted for school education. Read the quadrants as use-modes, not device types: classes can move between them during a single activity.

just see the annotations. They walk the same investigative paths, develop spatial memory tied to their own movement, and experience scale relationships through their body rather than through mouse orbits and zoom controls. The persistence is not merely visual but embodied: learners remember "where we looked from when we discovered X" rather than "which view angle we selected".[35] This distinction matters for distributed collaboration because spatial understanding developed through embodied exploration creates different knowledge artifacts than spatial understanding mediated through screen-and-mouse manipulation. The time-space matrix becomes fully addressable when collaboration retains not just spatial structure but the egocentric, body-scaled experience of navigating that structure across sessions and sites.

Finally, multi-user XR supports collaborative sensemaking through gesture, gaze, and shared manipulation: communication channels absent in video calls or text forums. When students point, grasp, or walk around a shared object, they coordinate attention and negotiate meaning through embodied cues that align with social constructivist accounts of learning, where knowledge emerges through joint activity and negotiation.[30] The spatial dimension of collaboration matters: as Harrison and Dourish argued for collaborative systems more broadly, technologies must support not just shared space but shared place, where meaning emerges from situated practice.[26] For distributed classrooms, this embodied co-presence offers richer interaction than video alone, while for co-located groups it can reveal collaborative patterns invisible in traditional settings.

These affordances do not guarantee learning gains. Poor design can waste them entirely. But they open possibilities unavailable through conventional tools: embodied understanding of complex systems, asynchronous spatial collaboration, and distributed sense-making that leverages physical intuition. For XR to become infrastructure rather than novelty, these affordances must be systematically aligned with curricular goals and learning theory, not treated as spectacle.[8] The sections that follow map how current practice aligns with these possibilities and outline pathways for vision-driven development that serves educational aims rather than technological enthusiasm.

3 Where schools stand today

3.1 Evidence-based status quo

Any credible vision for the future of education must begin with a pragmatic assessment of the present. Suppose XR is to address systemic challenges effectively. In that case, its design must be rooted in the digital realities of schools: what resources are available, how they are utilised, and where gaps still exist. The Programme for International Student Assessment (PISA) data of 2022 shows the following pattern: German schools now average 0.57 PCs per student (OECD 0.87) and 0.56 tablets (OECD 0.36). Teacher access rose to 0.82 internet-enabled computers per teacher since 2018, driven by DigitalPakt and pandemic procurement. Yet only 12 % of students use computers daily at school (OECD 36), and learning software is used daily by 11 % while 40 % never use it. At home, ownership of computing devices (PCs, smartphones and tablets) and internet access are near universal (near 95 %), but only 60 % report owning educational software (OECD 75 %). While hardware has improved, day-to-day, collaborative use has not.[36]

Recent systematic reviews of XR in education reveal both promise and persistent methodological challenges. Jensen and Konradsen found that head-mounted displays support spatial and visual skills acquisition but offered no advantage over less immersive technologies for other cognitive tasks, with some studies showing counterproductive effects due to cybersickness or distraction.[37] Radianti et al. observed that most VR applications in higher education remain experimental rather than curricular, with evaluations prioritizing usability over learning outcomes and few grounding their design in learning theory.[38] Lawson et al. examined media comparison studies in STEM education and found that many lacked sufficient experimental control, making it difficult to attribute learning gains specifically to immersive features rather than confounding instructional differences.[39] These reviews converge on a shared concern: the gap between XR's technical capability and its reliable, theory-driven integration into sustained pedagogical practice.

Rhineland-Palatinate's "Schule der Zukunft" (School of the Future) illustrates both promise and friction in pedagogy.[40] About a hundred schools are testing flexible timetables, learning offices for self-paced work, and teachers in a coaching role. Supporters report greater student agency;[41] critics, including the *Philologenverband*, a conservative umbrella organisation for teachers in Germany, warn that loosening class structures can erode guidance and community.[42] Disputes over grading policies show how basic questions of assessment remain unsettled. Evidently, even without new technologies in focus, German schools struggle to balance innovation with tradition, which is the landscape any XR approach must respect.

Many XR projects spark strong initial engagement, but recent evidence suggests a more nuanced trajectory as novelty recedes. In a three-session VR lab study, novelty dampened initial memory formation while recognition improved by session three, with cued recall unchanged.[43] Semester-scale field data from a 15-week social VR class show that more time in VR relates to higher instructor and peer social presence and to higher perceived competence and enjoyment; peer social presence and competence peak around 40–50 min on average with large individual variance, and longer VR also increases virtual meeting fatigue.[44] Taken together, as XR becomes routine and sessions are right-sized, the novelty penalty shrinks and the medium becomes more efficient for collaborative learning. Schools are not only a place to acquire knowledge. They are a socially dense setting where young people negotiate norms, empathy, and agency. PISA 2022 data suggest that the bottlenecks in Germany are less about devices and more about sustained, meaningful use, as well as the time and support teachers need to integrate digital activities. Any XR roadmap should therefore ask a social question first: which interactions truly require physical presence, which can be transitioned to shared virtual spaces, and which benefit from asynchronous rhythms. Adaptability in schools is also limited. Few teachers have the time or skills to modify XR content at pace, and many lack confidence with unfamiliar tools.[45] The teachers' intention to use classroom technology depends on perceived usefulness and on facilitating conditions such as support and planning time.[46,47] Strong analogue preparation skills, such as creating custom worksheets and hands-on activities, do not automatically transfer to complex digital environments. Resistance often stems not from teaching competence, but from the pressure to replace trusted methods as the workload rises. Also, many teachers have little prior contact with immersive applications and report hesitations; multipliers and practice-oriented exemplars are needed to move beyond isolated pilots.[8] Recent XR didactics work highlights the need for worked examples (step-by-step demonstrations), teacher-editable materials, and classroom orchestration strategies to lower entry barriers.[48]

A persistent tension between teacher-centred and student-centred approaches reinforces these barriers. Limited preparation time and lack of support make it easier to continue with familiar, teacher-directed instruction, even when collaborative or exploratory methods might be more engaging. Structural factors deepen the reliance on teacher-directed instruction. Rigid curricula leave little room for experimentation, assessment systems prioritise standardisation over process-driven learning, and timetables discourage extended projects. The result is a growing gap between the possibilities of emerging technologies and their practical use, a gap that vision-driven XR must close to move beyond isolated demonstrations towards sustainable impact.

3.2 Mapping German schools onto the time–space matrix

These limitations are visible when German schools are mapped onto the time-space matrix. The ST/SP quadrant dominates: most learning is anchored in traditional classrooms with occasional enrichment through immersive technology. A clear example is our developed mixed-reality station of the TouchTomorrow-Truck that reaches around 10,000 students each year.[49] At a shared table, small groups use video-passthrough headsets and hand tracking to place process tokens and simulate a self-driving car factory in an eight-minute session that logs interactions for later analysis (cf. Figure 3). Comparable research environments, such as room-scale immersive labs, show strong potential but often require specialised facilities. Universities are also exploring co-located multi-user lessons. TU Dresden's Future Classroom (EduXR) develops headset-based co-located XR lectures, where students manipulate shared objects in real-time.[50]

Alongside such co-located demonstrations, a recent VR deployment in German schools illustrates how procurement-led initiatives approach the problem space. In 2024, the Ministry of Education in North Rhine-Westphalia (NRW) funded around 3,000 VR headsets for schools. The pilot deployment paired the VR devices with an XR-SaaS platform for classroom control and centralised device management. The accompanying media library aggregates many third-party applications and filters them by topic, yet there is little explicit mapping to the curricula of any federal states, and most content targets a single headset family.[51] While the pilot materials cite a consultancy report to justify higher focus and faster learning, the study examined adult employees in short soft-skills trainings, relied primarily on immediate self-reports with one 30-day check, and only lists a few scholarly references. As such, it should be treated as grey literature that does not provide conclusive evidence for sustained engagement in primary and secondary schools.[52] We treat this as a representative example of procurement-led, platform-plus-hardware offerings in education. Such initiatives can seed activity and reduce setup burden, and the intent to bring VR into schools is commendable. Yet, without curriculum alignment, shared interaction conventions, and independent evaluation, they risk leaving teachers to navigate a patchwork of

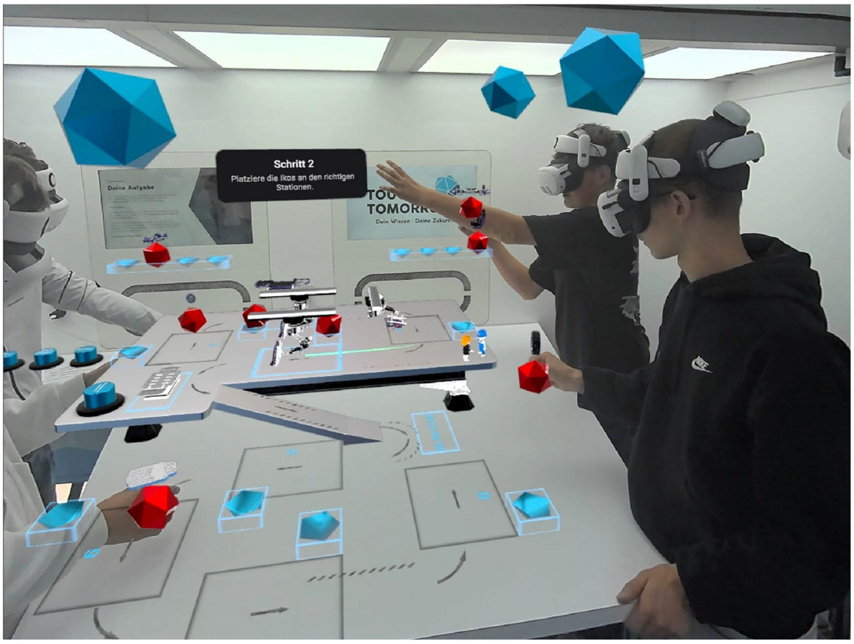

Figure 3: Students working on the Mixed Reality station of the TouchTomorrow-Truck. This co-located, synchronous setup (ST/SP quadrant) reaches 10,000 students annually but illustrates the current bias: most XR in schools remains confined to same-time, same-place demonstrations rather than persistent or distributed learning.

heterogeneous apps, limiting reuse across schools. Taken together, these paths strengthen ST/SP but do not yet unlock asynchronous collaboration.

To move beyond ST/SP into distributed collaboration, the ST/DP quadrant needs more than video calls. Several research toolkits show what is possible. For example, Anthony Steed's Ubiq-Exp demonstrates how remote and distributed mixed-reality sessions can support shared objects across sites, with logging, record-and-replay, user and scene management, lobbies and avatars.[53] EduXR also has piloted hybrid XR lessons where remote school groups co-create with on-site participants.[54] These examples suggest that XR can let schools share teaching resources and student cohorts across distances with far greater immediacy than video conferencing alone.

The DT/SP quadrant remains rare in everyday practice. Classrooms are typically reset between sessions, breaking continuity for long-term group work. The Dresden University School offers a glimpse of what persistence looks like in a real school trial: a public community school jointly run by the City of Dresden and TU Dresden, where all-day, project-based learning is tested under scientific supervision and used for teacher training. As a 15-year, research-supervised school trial, it can redesign timetable, assessment, and digital documentation; these routines already formalise continuity and handover without XR, which should ease later integration. It is a living example of continuity structures even without XR, which makes it a natural target for mixed-reality extensions. Combined with AI-driven object recognition and digital twin techniques, such models could enable students to "pick up where they left off" in the same physical space.

Research on persistent and asynchronous XR shows the core mechanics already exist: room-anchored content that survives sessions, perspective-preserving objects, and record-and-replay of scene state. Blocks demonstrates co-created AR structures that persist across time and place;[35] Ubiq-Exp provides logging and replay features usable across sessions.[53]

Finally, the DT/DP quadrant is the least developed in schooling. Some LMS platforms support asynchronous collaboration, but rarely in an interactive, project-based form. Research prototypes with spatial annotation and asynchronous replay, such as the so-called MemoryPods, explore how contributions can be revisited and extended.[55] At the European level, XR4ED pilots test AI-supported tutors in shared VR labs, enabling students in different time zones to contribute at different times.[56]

Taken together, the mapping reveals a system primarily oriented toward synchronous, co-located interaction, with asynchronous and distributed modes still largely unexplored. However, research and pilot projects across Germany and Europe are already exploring these underused quadrants, providing a credible foundation for vision-driven XR development that enhances collaboration, continuity, and personalisation.

Having mapped where German schools stand today, we now turn to development pathways that could expand educational practice across all four time-space quadrants. The scenarios that follow are research trajectories contingent on addressing the barriers identified above, not predictions of linear progress.

4 Development horizons and pathways by quadrant

Figure 4 outlines potential research trajectories for XR integration in education rather than predictions of specific technologies or adoption dates. Each horizon represents a plausible development pathway contingent on addressing technical, pedagogical, and systemic challenges identified in Section 3. The scenarios serve as design targets for researchers and policymakers, not forecasts of inevitable outcomes. Each coloured layer in Figure 4 represents cumulative progress: foundation building (light orange) establishes core infrastructure, hybrid integration (orange) connects distributed learners, and long-range transformation (dark orange) achieves full matrix coverage.

By a *horizon* we mean a time-sequenced layer (10–15, 25–35, 50 years) that cumulatively expands coverage of the time–space matrix. Within each horizon, a *pathway* is the within-quadrant sequence: problem → mechanism → milestones that links technical capabilities, teacher workflows, and governance so XR moves from pilots to routine use.

Exemplary pathways:

- ST/SP: High prep time → teacher-editable nuggets + classroom orchestration → scene persistence and remix across lessons.
- DT/SP: No continuity between sessions → room anchors + versioned state → "pick-up-where-you-left-off" projects.
- ST/DP: Thin remote labs (lightweight browser-based interfaces to physical equipment) → shared manipulable 3D objects across sites → routine interschool practicals.
- DT/DP: Gaps between sessions → AI peers in persistent scenes → handover logs/provenance and asynchronous co-creation.

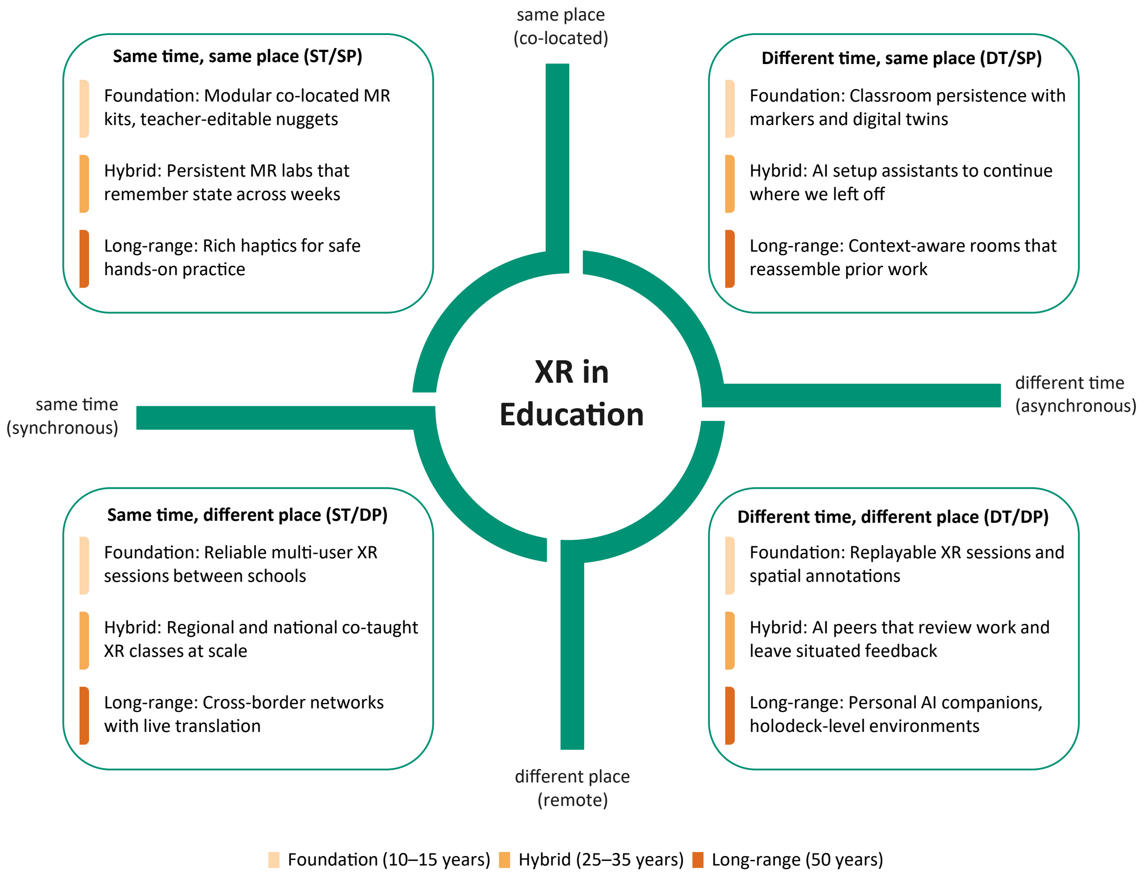

Figure 4: XR development horizons across four collaboration modes. Each track addresses distinct technical challenges (persistence for DT/SP, synchronization for ST/DP, etc.) but should converge toward fluid transitions: learners switch from asynchronous AI-supported work to synchronous human collaboration without leaving the same environment. The scenarios are research trajectories, not predictions.

4.1 10–15 years: foundations for ST/SP and first openings in DT/SP, ST/DP, DT/DP

The first stage is not about futuristic hardware. It is about translating existing research into tools that support richer learning activities while remaining easy to set up, editable by teachers, and persistent across lessons. That consolidates ST/SP first, while opening dependable paths into the other three quadrants. Co-located work will progress the fastest because it already aligns with school routines. At the previously mentioned mobile Mixed Reality (MR) station, students place tokens on a shared table and observe a simulated production flow respond in real-time.[49] If treated as so-called nuggets (self-contained, reusable VR or AR modules built from educational design patterns),[57,58] these interactions are easily transferred to science labs or geography fieldwork with minimal retargeting. Modularity slows down ageing, improves the effort-to-lifespan ratio, and allows teachers to remix scenes without starting from scratch. Evidence from reusable learning-object research supports this logic: when granularity and metadata are well designed, preparation time falls and reuse across courses rises, though the effect depends on object quality and repository design.[59,60] Modular nuggets align with four VR activity patterns discussed in media didactics: training worlds, construction worlds, exploration worlds, and experimental worlds.[8] Recent German training examples include HandLeVR's paint-shop simulator, which provides immediate feedback during procedural practice.[61]

In practice, a blended lesson plan would interleave conventional and XR-supported phases. A teacher might open with a brief whole-class introduction at the board (ST/SP, no headset), then hand over to a ten-minute XR exploration phase in which small groups manipulate a shared simulation while the teacher monitors progress through a dashboard view. After headsets are removed, the class reconvenes to discuss findings, compare observations, and consolidate understanding. Assessment can draw on two complementary sources: the spatial interaction logs captured during the XR phase (e.g. object placements, token sequences, collaboration patterns) and the conventional artefacts produced afterwards (written reflections, group presentations, worksheets). Orchestration tools should let teachers pause, annotate, and fork scenes mid-lesson, so that the transition between analogue and digital phases feels as routine as switching between a textbook and a lab bench. This blended structure respects existing lesson rhythms while giving the XR phase a clear curricular function rather than treating it as a standalone event.

Schools need both platform and pedagogy. An XR layer should handle shared anchors, identity, persistence and low-latency sync via open interfaces, serving all quadrants. It should also fit reform models such as learning offices without excluding direct instruction. The goal is flexibility: teachers can coach or lead, and scenes persist across sessions and places. Cross-site links introduce friction (language, curriculum alignment, scheduling across time zones), but they also let schools share scarce expertise and expose students to perspectives unavailable locally.

Persistence now extends beyond headsets.[14] As classrooms add sensors and inexpensive microcontrollers, physical objects can be complemented with digital twins.[62] Versioned scene states, timestamped differences, and role-based logs enable groups to leave work for others to continue, and allow teachers to roll back, fork, or compare attempts. This is the practical step from the already established Internet of Things (IoT) to an Internet of Everything (IoE) in school settings, where changes in the physical room or in the virtual scene inform each other and can be tracked across weeks.[63] AI support should begin as a means of workload relief, rather than as a replacement for teaching. Assistants can check devices, test sessions in advance, adapt existing materials into scenes and suggest nugget combinations that fit a plan. With that scaffolding in place, schools receive fewer one-off demonstrations and more lessons that can be repeated, shared, and maintained. In Buxton's terms, this is research turning into innovation.[3] In 10 to 15 years, XR should have shifted from an occasional showpiece to a dependable tool.

4.2 25–35 years: hybrid integration of ST/DP and DT/DP

With foundations in place, XR can evolve from primarily co-located applications toward a fully integrated hybrid model. The focus shifts from isolated sessions to persistent, shared environments that support both synchronous and asynchronous learning across multiple sites. Hybrid integration advances the ST/DP and DT/DP quadrants, enabling classes to meet and continue work across different locations and schedules.

As platforms mature, the ST/DP quadrant can support distributed classes that manipulate shared objects in real-time,[50,54] potentially evolving into regional or international networks where schools pool expertise without geographic constraints.

At the same time, AI peers for asynchronous collaboration begin to populate persistent environments, addressing the DT/DP quadrant.[64] These agents act as collaborative partners who review work, pose questions, and contribute ideas when human classmates are offline. Because they inhabit the same spatial context as learners, interactions feel closer to working with a partner than to using a tool.[65] Asynchronous collaboration becomes richer, more personalised and less dependent on constant teacher supervision. Smooth transitions between immersion and video passthrough should allow learners to move seamlessly between VR and MR during a single activity, enabling remote and co-located groups to remain in the same scene without disrupting the flow.

In parallel, course-bound companions will emerge. These are profile-aware agents tied to a student account or portfolio that persist across a term and accompany the learner from one session to the next. They provide practice, feedback and translation, and they retrieve and display prior work inside the same scene. They remain bounded by school policy and teacher oversight and do not replace human facilitation.[66,67]

Hybrid integration exposes the need for the matrix's fluid edges. A group may work asynchronously with AI personifications that leave spatial notes and tentative analyses, then shift to live collaboration the moment peers come online. When a learner, who was previously represented by an agent, joins, the agent hands over state and provides a summary of actions taken, while provenance is kept.[68] The returning learner reviews what occurred and decides how to proceed, ensuring they remain accountable for understanding the work rather than simply inheriting outcomes. Platforms should make these handovers routine, so activities slide between DT/DP, ST/DP and ST/SP without resets, content loss or safety issues.

Persistent digital learning environments support both modes. Unlike most current apps that reset between sessions, these spaces maintain state, preserving contributions, artefacts, and discussion histories, expanding the capabilities of research apps like Blocks.[35] Multi-week or semester-long projects become natural, similar to project-based models today, but extended into mixed-reality contexts. Teachers can access these environments at any time to monitor progress, make adjustments, and introduce new challenges without needing to rebuild environments.

This stage represents the innovation-to-mainstream transition in Buxton's timeline.[3] Technology reliability will be necessary, but its impact will depend on the ecosystems and pedagogies surrounding it: interoperability, curriculum alignment, flexible assessment, and sustained professional development. Didactic approaches and learning platforms must evolve together, neither can succeed in isolation. By the end of this horizon, XR should feel like a seamless extension of the classroom.

4.3 50 years: balanced occupancy of all quadrants

The 50-year horizon should be read as a speculative research agenda rather than a forecast. The precise technologies are unknowable, and the scenarios outlined here serve to identify long-term research challenges and governance needs rather than to predict specific implementations. However, certain recurring pressures are likely to persist in some form: uneven distribution of teaching expertise, increasingly diverse and multilingual classrooms, persistent inequalities in access, accelerating knowledge cycles and global crises that demand resilient, collaborative systems. The 50-year view aims for balanced occupancy of all four quadrants, so that learners and teachers can choose the mode that best fits the task, the timetable, and the geography.

In this horizon, XR's role is to provide adaptive, personalised learning environments at scale. In the long view, all four quadrants become routine choices, selected by necessity rather than technical limitations. Full implementation of the time-space matrix could become a daily reality, with students shifting fluidly between co-located and distributed learning, and between synchronous and asynchronous participation, as their needs and schedules change. Advanced human-machine interfaces, potentially including brain-computer integration,[69] may open new interaction modalities, particularly for learners with disabilities, though development would require robust safeguards for privacy, informed consent, and mental well-being.

Advances in materials and haptics could bring schooling closer to holodeck-like[70] practice:[71] virtual objects offering believable force and texture, assembled with realistic tolerances and safe repetition. Layered with reactive AI, story worlds branch with student choices, record provenance and resist shortcutting. The aim is not spectacle but dependable narrative scaffolding for inquiry while AI manages pacing, translation and fragile state.

Personalised AI companions may evolve into lifelong learning partners. Unlike today's short-term, account-bound agents, these companions would maintain a deep, portable history, adapt across institutions and devices, and run largely on the learner's personal device for privacy and control.[64] They would act as co-educators by tracking long arcs of progress, coaching across subjects and smoothing transitions between virtual and physical work. Periodic synchronisation with institutional systems would update them on curricular changes and pedagogical guidelines, while teachers retain responsibility for judgment, culture, and care.

The skills that gain value are clearer when separated into two groups. First are modelling and simulation literacy, and the ability to collaborate across time and place. Added to these are AI literacy with a critical stance, careful habits around data provenance and privacy, and embodied making that links physical and virtual media. By contrast, routine explanation, first-pass grading, and basic task sequencing are likely to be automated. As AI companions handle much of what we now call instruction (explanation, practice, assessment, adaptation), the human role shifts from primary knowledge source toward mentor, socialiser, and ethical guide. Whether this transition preserves what matters most about schooling, or erodes it, remains an open question that governance structures must address rather than ignore. In this horizon, XR is judged by how well it strengthens distinctly human capacities while safely offloading routine tasks. Success depends on groundwork laid in earlier decades: adaptable platforms, equitable infrastructure, and curriculum-aligned XR designs that teachers use week by week, not just for special demos. Without these conditions, even advanced systems risk low use once the novelty fades.

Most significantly, global XR learning networks could loosen the tie between education and a fixed physical institution, even more so than online schools do today. Students might belong to international academies that operate continuously, connecting peers from different countries in shared, long-term projects. Physical schools could remain as community hubs for practical work, social interaction and hands-on experimentation, supported by a mesh of distributed XR spaces. Real-time translation will lower barriers, but language could still function as a cognitive tool, a cultural commitment, and a marker of identity. In a global classroom, expect one or two common working languages for shared STEM projects, alongside deliberate language choices tied to community, subject matter, and equity goals.

Realising any of these trajectories depends on overcoming linked technical, pedagogical, and societal obstacles. We now examine these implementation challenges and the governance structures needed to ensure XR serves educational aims.

5 Implementation challenges and governance

The scenarios in Section 4 describe how XR could expand educational possibilities over the next five decades. Realising any of them will depend on overcoming a set of linked obstacles. These challenges are not abstract; they arise directly from the gaps and constraints described in Sections 3 and 4. Unless addressed early and systematically, promising technologies will remain confined to isolated pilots, failing to reach the scale and sustainability required for long-term impact.

These challenges unfold within broader systemic pressures. Sustainability concerns include the environmental cost of hardware production and disposal, energy consumption of XR infrastructure, and the tension between rapid device churn and durable pedagogical investment. Digital sovereignty questions arise as educational data and platforms concentrate in few multinational providers, raising issues of data localization, algorithmic transparency, and national control over educational technology. Global governance frameworks remain fragmented, with divergent data protection regimes (GDPR in Europe, varied approaches elsewhere) complicating cross-border collaboration. Addressing XR implementation in education thus requires coordinating technical development with policy frameworks that balance innovation, equity, and sovereignty.

5.1 Technical

Sustaining engagement beyond the novelty phase is difficult, and methodological weaknesses in the evidence base compound uncertainty. Lawson et al. found that many IVR comparison studies in STEM education failed to control for confounding instructional differences, making it unclear whether learning gains stem from immersive affordances or from better-designed activities.[39] Early deployments often attract high participation, followed by a decline in usage as technical limitations, repetitive content or shallow integration erode interest. In recent years, this has also occurred with interactive whiteboards.[72] National rollouts advanced despite strong classroom evidence and achieved high penetration.[73] Teachers then faced thin, non-tailored materials and time pressure, so boards were used mainly as a projection surface.[74,75] Instead of focussing on partner- and group-work, the fixed front-of-room placement pulled practice back towards frontal teaching.[76] Underlying causes recur across studies: limited training and ongoing support, scarce preparation time, technical instability, and weak alignment with pedagogy and school culture.[77,78] Abandonment from teachers is more likely when complexity and workload outweigh perceived usefulness and ease of use.[79]

Infrastructure is a second bottleneck. Reliable high-bandwidth connectivity, device compatibility, and low-latency multi-user synchronisation are prerequisites for hybrid and persistent environments.[45] In Germany, device availability has improved, but daily instructional use and the time and support teachers need to integrate digital activities remain limited.[36] Even where hardware is funded, maintenance, updates, and technical support are often under-resourced, which degrades reliability over time.[36] Interoperability also remains unresolved: in the 2024 NRW pilot, thousands of headsets were paired with a single XR SaaS platform and a media library tied mainly to one headset family, with little explicit mapping to state curricula, raising portability and lock-in risks.[51,52] Without agreed standards for content and device interfaces, schools risk vendor lock-in and fragile, short-lived formats.

Classroom management is a practical prerequisite for scaling XR. Systems used in schools need controls comparable to managed tablets: class-wide pause, lock to the active scene, per-learner view, one-click reset, allow-lists, and basic activity logs. Without these, day-to-day use tends to drop as teacher workload and coordination costs rise.[36] Designs should assume uneven readiness across schools and specify minimum competencies and safeguards rather than a single device path.

5.2 Pedagogical

Adaptation is not about devices. It requires shifts in practice. Many experienced teachers face steep learning curves, not from lack of competence, but from adapting established workflows under time pressure. Professional development should respect existing expertise and be built incrementally. XR should be treated as augmentation, not replacement. In the near term, AI should be used for practice, explanation, and translation under teacher oversight, while teachers retain evaluation, grading and pastoral care. Companions in the next decade will be account-bound rather than lifelong; they should inherit only course context, expose their reasoning to teachers and learners, and escalate social or ethical decisions. Reliable identification of such moments remains an open problem; conservative triggers and human review will be necessary until detection matures. Consistent with media-didactics guidance, XR design should prioritise learning tasks and activity structures over device features. Spectacle without curricular fit rarely sustains use.[8]

A tension emerges between spectacle-oriented deployments and routine, goal-aligned activities. In semester-scale observations, social presence and perceived competence peak at moderate session lengths while fatigue increases with longer exposure; as familiarity grows, longer sessions appear more feasible.[44] Combined with short-run novelty effects that fade across repeated sessions,[43] these patterns are consistent with designs that embed repeatable interactions tied to content objectives yielding more durable gains than attention-capturing novelties.

The international dimension raises the stakes. Germany already juggles 16 curricula, one for every federal state; a global classroom adds cross-border standards, consent rules and content politics. A practical path is to anchor projects in shared competencies and artefacts, then map them to local syllabi, supported by portable learner records and teacher review. Participation will be uneven due to infrastructure or policy, so designs should accommodate tiered access, offline-first options and transparent data governance. Without assessment reform, systems built around standardised tests, and subject silos will misinterpret collaborative, process-driven learning and XR will be dismissed as a distraction.

5.3 Societal

XR systems can capture sensitive biometric data, including head and hand movements and eye gaze, and in the future possibly neural signals.[23,69] Without robust governance, such data can be misused for profiling, surveillance, or behavioural prediction.[23] Public trust will depend on transparent policies, informed consent, and independent oversight. Algorithmic bias is a further risk. AI-driven tutors and adaptive simulations reflect the assumptions and data of their creators; without safeguards, they may marginalise specific learners or reinforce stereotypes. Finally, equitable access remains essential. Differences in funding, infrastructure, and staffing produce uneven opportunities even within well-resourced countries; in Germany, device availability has risen while everyday learning use and support lag.[36] Policies for affordability, shared infrastructure, and open content are needed if XR is to close gaps rather than widen them.

5.4 Unintended consequences

XR can address problems while introducing new risks. Health concerns include simulator sickness and eyestrain; prolonged exposure can increase virtual-meeting fatigue, which is negatively associated with perceived learning, competence, and enjoyment.[44] Over-virtualising practice could weaken safety habits in labs or fieldwork if it replaces hands-on work rather than preparing for it. Equity is a major risk: without design for affordability, offline use, and shared infrastructure, advanced XR will concentrate in already advantaged schools.[36]

6 Conclusion: build for problems, not gadgets

If XR is to matter over the next 25–50 years, its development must be grounded in today's classrooms and guided by clear problems. Ishii reminds us to start with persistent human needs, not devices, and Buxton shows that mainstream impact follows long periods of refinement. Without sustained focus on genuine educational challenges, impressive prototypes will not endure.

History shows that tomorrow's breakthroughs are prepared years in advance. Much of what we use now, from multi-user XR spaces to adaptive AI, matured quietly in labs. Progress stalls when capability outruns conditions of use: teachers are not trained, software is too narrow, and infrastructure is installed but not maintained. Devices gather dust and enthusiasm fades.

The priority is to fix the conditions. This means closing the gap between hardware and meaningful use, making content more adaptable, and providing preparation time and technical support. It also means aligning collaborative learning with assessment. Practical steps include reusable, adaptable lesson plans with integrated XR activities and materials, shared collaboration platforms, teacher-editable persistent scenes, and AI that assists in lesson design rather than replacing teaching.

Alignment across the system is essential. Researchers can build adaptable, modular applications instead of monoliths. Policymakers can set interoperability standards and value collaborative work in assessment. Educators' expertise should inform design from the start. Developers should target applications that survive device churn and respect the economics of lesson preparation.

There are foundations to build on. Reform movements such as the "School of the Future" offer a pedagogical anchor,[41] technical groundwork is emerging across Europe, and demographic pressures add urgency. The task here is not to predict gadgets. It is to shape XR as a human-centred, problem-driven infrastructure that expands collaboration, protects agency and privacy, and serves education's aims.

When those students in Bremen and Sejong meet in their shared rainforest decades from now, they will inhabit not a technological accident but a carefully cultivated space, built through today's groundwork: modular tools teachers can actually use, standards that outlast devices, and a steady focus on human learning over device sophistication.

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