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Expanding Spatial Understanding through Mobile Augmented Reality: A Contemporary Synthesis of Pedagogical, Technological, and Cognitive Dimensions in Geography Education

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Abstract *Mobile augmented reality (AR) has evolved from an experimental visualization tool into a mature pedagogical medium that redefines spatial learning in geography education. By embedding digital content into authentic locations, AR fosters experiential and inquiry-driven learning aligned with geography's spatial and environmental paradigms. Building on evidence from 2015 to 2025, this review synthesizes 138 studies to examine how AR supports cognitive, affective, and behavioral learning dimensions. The analysis reveals that AR enhances spatial reasoning, visualization of abstract processes, and place-based engagement when integrated within robust instructional design frameworks. However, persistent gaps remain in long-term learning assessment, scalability, and teacher competence for authoring AR experiences. Cognitive-load and motivation studies suggest that AR's benefits are maximized when interactivity and spatial anchoring are balanced with scaffolding. The review proposes a multidimensional model linking technological affordances, pedagogical strategies, and geographic thinking to promote education for sustainability and digital spatial citizenship. Implications for researchers, educators, and developers are discussed to guide future cross-disciplinary innovations.*

Keywords: *Augmented Reality; Geography Education; Spatial Learning; Pedagogy; Immersive Technology; Sustainability Education*

1. Introduction

The rapid expansion of information and communication technology (ICT) continues to reshape how students engage with knowledge and space. Mobile devices—now equipped with sensors, cameras, and global positioning—enable immersive experiences that merge digital and real-world contexts (Fraillon et al., 2020; Mikropoulos, 2018). Among these, augmented reality (AR) uniquely situates digital information within the learner's immediate environment, allowing three-dimensional (3D) interaction with otherwise invisible geographic processes (Azuma et al., 2001; Wu et al., 2013).

Over the past decade, a surge of empirical work has demonstrated AR's potential to enhance science, technology, engineering, and mathematics (STEM) education (Altinpulluk, 2019; Pellas et al., 2019; Mystakidis et al., 2022). Yet geography education—despite its inherent spatial and environmental focus—has only recently received systematic attention (Schmidt & Stumpe, 2025). Geography's dual concern with *space* and *place* positions it as an ideal disciplinary arena for AR integration: spatial visualization can transform abstract physical systems into experiential, context-anchored understanding (Taylor, 2005; Larsen & Harrington, 2018).

This review modernizes and extends prior syntheses by critically integrating newer evidence (2018–2025) on mobile AR, cognitive load, motivation, and pedagogical design. Rather than reiterating earlier descriptive overviews, it constructs a narrative synthesis of technological affordances, pedagogical strategies, and cognitive implications that collectively inform effective geography instruction. By situating findings within broader debates on digital spatial citizenship (Jekel et al., 2015) and sustainability learning (Metag, 2019), the paper seeks to reposition mobile AR as both a cognitive and ethical framework for twenty-first-century geographic literacy.

2. Theoretical and Pedagogical Framework

2.1 From Mixed Reality to Situated Learning

AR resides along Milgram and Kishino's (1994) mixed-reality continuum, occupying the zone where virtual and physical environments coexist. Unlike fully immersive virtual reality (VR), AR retains learners' interaction with their real surroundings while embedding digital objects within them (Azuma et al., 1997). This *hybrid immediacy* creates conditions for *situated cognition*—learning that is contextually anchored and socially mediated (Brown et al., 1989). Mobile AR extends this principle through ubiquitous devices that bring contextual data into fieldwork, thereby linking classroom theory with outdoor inquiry (Chang et al., 2022; Garzón et al., 2020).

The pedagogical significance of this alignment lies in geography's *signature pedagogies*—inquiry-based learning and fieldwork (Bourke & Mills, 2022). Mobile AR allows these pedagogies to evolve from static map-reading to dynamic interaction with layered spatial representations. Through sensor-based interfaces, learners can investigate phenomena such as erosion, land use, or atmospheric circulation by visualizing them *in situ*. As Priestnall (2020) argues, AR thereby becomes "inherently geographical," amplifying kinaesthetic engagement and sense of place.

2.2 Affordances of AR in Educational Contexts

Wu et al. (2013) identified five affordances of AR that underpin its pedagogical impact: (1) learning with 3D perspectives; (2) ubiquitous, situated, and collaborative learning; (3) sense of presence and immersion; (4) visualization of invisible or abstract phenomena; and (5) bridging formal and informal education. Later studies confirm these affordances while emphasizing design variables such as interactivity, feedback, and task authenticity (Radu, 2014; Garzón, 2021; Sırakaya & Alsancak Sırakaya, 2022).

In geography, these affordances converge with disciplinary needs. For instance, (1) 3D perspectives support spatial reasoning by allowing learners to manipulate terrain models; (2) situated collaboration facilitates shared exploration of local sites; (3) presence heightens emotional connection to place; (4) visualization elucidates invisible processes like groundwater flow; and (5) bridging contexts enables continuity between classroom and field. Collectively, these affordances suggest that effective AR design in geography education must move beyond novelty toward intentional pedagogical orchestration.

2.3 Constructivist and Cognitive Foundations

Constructivist learning theory positions learners as active constructors of knowledge through interaction with their environment (Vygotsky, 1978). AR environments exemplify this by merging sensory, motor, and conceptual engagement. However, cognitive-load theory (Sweller, 1994) cautions that the addition of multimodal elements can either scaffold or overwhelm working memory. Empirical research demonstrates that when AR experiences include clear instructional cues and manageable interactivity, intrinsic and extraneous loads are balanced (Lai et al., 2019; Buchner et al., 2021). Conversely, unstructured AR environments risk cognitive overload, especially among novice learners (Alzahrani, 2020).

Recent meta-analyses (Ozdemir et al., 2018; Bower et al., 2014) confirm significant learning gains from AR relative to traditional methods but highlight heterogeneity in effect sizes linked to subject domain and learner age. In geography education, these cognitive considerations intersect with spatial literacy development—students must integrate symbolic, visual, and embodied modes of reasoning. Hence, AR's pedagogical promise depends on the degree to which designers align multimodal stimuli with meaningful spatial tasks.

Table 1. Principal affordances and theoretical foundations of mobile AR in geography education

Affordance / Theoretical Link	Pedagogical Function in Geography	Representative Outcomes	Key Mediating Factors	Ref.
3D Perspective Learning (3DP)	Enables manipulation of terrain, landform, and process models; promotes spatial visualization	Improved conceptual understanding of scale, relief, and spatial relations	Interaction design; fidelity of visualization	Akçayır & Akçayır (2017); Garzón (2021); Schmidt & Stumpe (2025)

Situated & Collaborative Learning (USC)	Connects classroom and field via GPS-anchored inquiry; fosters teamwork and data sharing	Greater learner autonomy and engagement	Mobility, context authenticity, peer communication	Wu et al. (2013); Pellas et al. (2019); Priestnall (2020)
Sense of Presence & Immersion (SPI)	Encourages emotional connection to place; supports embodied cognition	Heightened motivation and empathy for environments	Feedback mechanisms, device usability	Billinghurst & Duenser (2012); Chang et al. (2022)
Visualization of Invisible Phenomena (VIU)	Makes latent geographic processes visible (e.g., pollution flow, plate movement)	Enhanced comprehension of dynamic systems	Cognitive scaffolding, clarity of representation	Garzón et al. (2019); Hidayat & Wardat (2024)
Bridging Formal–Informal Contexts (BFI)	Extends learning to museums, local sites, and digital citizen mapping	Sustained learning transfer and curiosity	Curriculum integration, teacher mediation	Da Silva et al. (2019); Buchner et al. (2021)

3. Technological Trajectories in Mobile AR for Education

3.1 From Marker-Based to Markerless and Location-Based Systems

Early AR applications in education were predominantly marker-based, relying on fiducial symbols (e.g., QR codes) to trigger digital overlays (Tacgin, 2020). While effective for controlled classroom tasks, such systems constrained spatial exploration. The subsequent shift to markerless and location-based AR—powered by sensors, accelerometers, and GPS—has been pivotal (Buchner et al., 2021; Dunleavy, 2014). In geography education, location-based AR enables learners to experience "augmented fieldwork," where environmental data are layered onto real landscapes (Hidayat & Wardat, 2024).

The democratization of software development kits (SDKs) such as ARCore and ARKit further expanded accessibility (Kljun et al., 2020). Educators now design localized content without advanced programming skills, aligning with open-educational-resource principles (Garzón, 2021). Yet the proliferation of easy-to-use authoring tools raises new challenges of pedagogical quality assurance and data ethics—issues increasingly noted in recent reviews (Beck et al., 2020).

3.2 Integration with Game-Based and Inquiry-Based Learning

The fusion of AR with game mechanics (ARG-based learning) has proven effective in sustaining engagement and contextual reasoning (Pellas et al., 2019; Costa et al., 2020). By embedding geospatial puzzles or quests within physical settings, learners enact inquiry cycles that parallel geographic investigation methods. Empirical results show significant improvements in motivation, problem-solving, and knowledge retention (Hwang et al., 2013; Papanastasiou et al., 2019). However, the alignment between game narrative and curricular objectives remains inconsistent, often emphasizing entertainment over conceptual depth (Altinpulluk, 2019).

In parallel, inquiry-based AR encourages hypothesis generation and data interpretation in authentic contexts (Da Silva et al., 2019). For example, learners may analyze pollution dispersion by observing virtual particle movements superimposed on actual rivers. Such experiences foster systems thinking but demand scaffolding to prevent superficial observation (Bower et al., 2014). The design implication is clear: AR should *extend* inquiry, not replace it.

3.3 Cognitive Load, Attention, and Motivation Dynamics

Cognitive-load research reveals nuanced interactions between visual complexity and learner expertise. Buchner et al. (2021) mapped 64 studies showing that mobile AR generally reduces extraneous load when visualizations correspond spatially with the real environment. Similarly, Lai et al. (2019) found that AR-based science reading significantly improved comprehension while lowering perceived mental effort compared to conventional multimedia. In geography, where spatial data are inherently multidimensional, these findings underscore the value of *contiguity*—placing related information in immediate proximity to the referent landscape.

Motivational studies align with these cognitive benefits. Meta-reviews (Alzahrani, 2020; Chang et al., 2022) consistently report enhanced engagement, curiosity, and self-efficacy in AR environments. Pellas et al. (2019) identified "flow" as a mediating factor linking interactivity and sustained attention. Nevertheless, excessive novelty or poor usability can reverse these effects, suggesting that motivational gains hinge on meaningful content rather than technological spectacle.

3.4 Toward a Pedagogical-Technological Model

Synthesizing these developments, three intertwined components characterize effective mobile AR in geography education:

a. Technological Infrastructure — reliable mobile hardware, spatial tracking accuracy, and accessible authoring tools;
b. Pedagogical Design — constructivist frameworks emphasizing inquiry, collaboration, and reflection;
c. Cognitive Regulation — optimized information load and scaffolding mechanisms.

When aligned, these components transform AR from a display technology into a *cognitive-ecological system*—a dynamic interface between learner, environment, and representation (Mishra, 2019). Such integration supports what Jekel et al. (2015) termed *education for spatial citizenship*: the capacity to interpret, critique, and ethically engage with digitally mediated spaces.

4. Empirical Synthesis: Evidence from 2015–2025

4.1 Overall Trends

Between 2015 and 2025, publications on AR in geography education increased sharply, mirroring broader growth across STEM (Garzón et al., 2020; Mystakidis et al., 2022). Most studies were conducted in primary and secondary settings, emphasizing physical geography, environmental systems, or spatial citizenship (Schmidt & Stumpe, 2025). Research in teacher education and sustainability themes is now emerging but remains comparatively limited.

Quantitatively, learning gains associated with AR are robust. Meta-analyses report medium-to-large effects on achievement, motivation, and spatial reasoning (Ozdemir et al., 2018; Chang et al., 2022). Yet heterogeneity persists, driven by differences in duration, device type, and pedagogical framing. Short-term interventions (1–3 sessions) tend to produce high affective responses but limited conceptual transfer; long-term curricular integration yields deeper spatial understanding but lower novelty effects (Garzón, 2021; Pellas et al., 2019). A recurrent methodological gap concerns the absence of delayed post-tests, constraining claims about retention and conceptual change.

Geographically, the literature remains dominated by studies from East Asia and Europe, particularly Taiwan, Spain, Germany, and Turkey (Buchner et al., 2021). Cultural contextualization of AR tasks—such as local heritage exploration (Arias-Espinoza et al., 2018) or sustainability fieldwork—receives less attention despite its potential to connect global and local geographies.

4.2 Cognitive and Affective Outcomes

Spatial Thinking and Conceptual Understanding

Spatial reasoning is the most frequently measured construct. Experiments indicate that AR-based manipulation of topography, tectonic motion, or weather systems yields superior comprehension compared to 2D maps or static models (Akçayır & Akçayır, 2017; Garzón et al., 2019). Students demonstrate improved ability to translate between representational modes text, map, and 3D visualization reflecting integrative spatial literacy (Ibáñez & Delgado-Kloos, 2018).

Cognitive-load findings refine this picture. Buchner et al. (2021) observed that mobile AR lowers extraneous load when digital objects correspond precisely to physical referents. However, misalignment or latency increases split-attention effects. Lai et al. (2019) confirmed that AR's contiguity and multimodal coherence can reduce perceived difficulty and improve learning persistence. Such evidence suggests that spatial congruence, rather than sheer realism, is the decisive variable for comprehension.

Motivation, Engagement, and Presence

Affective data reveal consistent enthusiasm among learners. Alzahrani (2020) and Chang et al. (2022) identify curiosity, enjoyment, and self-efficacy as the most enhanced dimensions. In geography contexts, presence—feeling "in place"—correlates strongly with motivation (Billinghurst & Duenser, 2012; Priestnall, 2020). Game-based AR amplifies this effect: location-anchored quests stimulate emotional investment in local landscapes (Pellas et al., 2019; Costa et al., 2020). However, sustained engagement declines when narrative or challenge design is weak. Therefore, affective outcomes depend on the integration of authentic tasks and meaningful spatial narratives.

4.3 Behavioral and Collaborative Learning Effects

AR's situated affordances support active, social learning. Studies show increased collaboration quality and peer explanation during AR-mediated fieldwork (Da Silva et al., 2019; Wu et al., 2013). The technology enables distributed cognition: learners share viewpoints through synchronized devices, constructing shared spatial frames. In secondary classrooms, collaborative AR mapping activities improved communication and critical discussion of environmental issues (Garzón et al., 2020).

Behavioral data from motion tracking and video analysis reveal deeper physical engagement compared with conventional instruction (Sırakaya & Alsancak Sırakaya, 2022). Students use gestures to align virtual models with real terrain, embodying spatial relations. Such kinesthetic interaction may underpin the observed gains in retention and transfer, echoing embodied-cognition theory. Nonetheless, device management and unequal access remain logistical obstacles, highlighting the need for equitable design.

4.4 Teacher Competence and Pedagogical Design

Teacher readiness emerges as a decisive factor. While authoring tools such as Vuforia and ARCore reduce technical barriers, pedagogical confidence and time constraints persist (Garzón, 2021). Many educators adopt pre-built apps rather than designing context-specific materials, limiting curricular integration (Bourke & Mills, 2022). Professional-development initiatives show that guided design projects enhance teachers' technological-pedagogical content knowledge (Mishra, 2019).

Schmidt and Stumpe (2025) argue that mobile AR's potential is constrained when technological affordances are detached from instructional principles. Empirical synthesis confirms that lessons combining explicit inquiry frameworks with AR yield the strongest outcomes. For example, place-based modules linking environmental data visualization to sustainability debates improve both conceptual understanding and civic attitudes (Metag, 2019; Andrei, 2012).

5. Discussion: Toward a Geography-Specific AR Pedagogy

5.1 Synthesizing Cognitive, Pedagogical, and Technological Layers

Across the reviewed evidence, effective geography-specific AR experiences share three design logics: **spatial alignment**, **narrative contextualization**, and **scaffolded interactivity**. Spatial alignment ensures cognitive economy by coupling virtual and physical referents; narrative contextualization transforms space into meaningful *place*; scaffolded interactivity regulates cognitive load while sustaining inquiry. These logics collectively define what may be called a *pedagogical-technological continuum* for geography AR.

5.2 Challenges and Tensions

Despite optimistic findings, several tensions limit large-scale adoption:

a. Fragmented Methodologies. Studies vary in metrics, making cross-comparison difficult. Few employ mixed-methods triangulation that captures both cognitive and affective change.
b. Equity and Access. Device quality and connectivity disparities undermine inclusivity, particularly in low-resource schools (Altinpulluk, 2019).
c. Pedagogical Superficiality. Some projects privilege visual appeal over inquiry depth, echoing technocentric pitfalls (Beck et al., 2020).
d. Data Privacy and Ethics. Location tracking introduces surveillance concerns, especially with minors.

e. Sustainability of Implementation. Few studies address long-term maintenance or institutional support structures.

These challenges underscore that technological innovation alone cannot guarantee pedagogical transformation; sustained professional learning and policy frameworks are equally crucial.

Table 2. Summary of key empirical findings and implications for geography education (2015–2025)

Focus Area	Representative Findings	Pedagogical Implication	Emerging Gap / Future Need	Ref.
Spatial Thinking	AR enhances 3D visualization and translation between representations	Integrate AR into map-reading and modeling units	Longitudinal tracking of conceptual change	Akçayır & Akçayır (2017); Garzón et al. (2019)
Cognitive Load	Spatial contiguity reduces extraneous load; poor design increases split attention	Apply multimedia-learning principles in AR authoring	Develop standardized cognitive-load measures for AR	Lai et al. (2019); Buchner et al. (2021)
Motivation / Presence	High novelty and immersion increase engagement	Embed authentic local narratives and field tasks	Examine long-term motivational sustainability	Chang et al. (2022); Pellas et al. (2019)
Collaboration	AR supports peer explanation and shared inquiry	Use cooperative mapping and annotation tasks	Investigate social-presence dynamics	Da Silva et al. (2019); Wu et al. (2013)
Teacher Competence	Limited design literacy constrains integration	Offer design-based PD and co-creation models	Study teacher learning trajectories	Garzón (2021); Mishra (2019)
Sustainability / Ethics	AR fosters place attachment but raises data concerns	Align AR with ESD and digital citizenship goals	Develop ethical design guidelines	Metag (2019); Jekel et al. (2015)

5.3 Linking AR to Spatial Citizenship and Sustainability

A distinctive contribution of geography education lies in its moral and civic dimensions. AR's capacity to visualize environmental change, overlay socio-economic data, and promote situated decision-making directly supports *education for sustainable development* (ESD). When learners explore augmented maps showing pollution dispersion or climate-risk zones, they engage with the consequences of human-environment interaction in tangible form (Metag, 2019).

Jekel et al. (2015) extend this vision through the concept of *spatial citizenship*, advocating critical awareness of how digital media construct space. AR becomes not only a representational tool but also a medium for interrogating digital narratives—who controls spatial data, which voices are amplified, and how augmented spaces influence behavior. Integrating these perspectives ensures that technological innovation contributes to ethical, participatory geographic literacy.

5.4 Integrative Model of Mobile AR in Geography Education

Drawing from the synthesis, the following conceptual model emerges:

a. Technological Layer: Hardware/software affordances enabling location-based interactivity.
b. Pedagogical Layer: Inquiry- and fieldwork-oriented instructional design promoting reflection.
c. Cognitive-Affective Layer: Balanced load, sustained motivation, and embodied engagement.
d. Civic-Ethical Layer: Spatial citizenship and sustainability consciousness.

The interaction among these layers forms a holistic ecology of learning. In practice, teachers can scaffold exploration phases—*observe* → *analyze* → *interpret* → *act*—supported by AR prompts and reflective discussion. Researchers should evaluate how transitions across layers affect learning trajectories and identity formation as "digital geographers."

6. Future Research Directions

6.1 Longitudinal and Comparative Designs

Future studies must move beyond short interventions toward semester-long or multi-year programs that track conceptual change, spatial reasoning development, and affective stability. Comparative cross-cultural research would illuminate how local geography and cultural values mediate AR engagement (Arias-Espinoza et al., 2018). Inclusion of control groups using traditional fieldwork would clarify additive versus substitutive effects.

6.2 Advanced Analytics and Mixed Methods

Emerging analytic techniques—eye-tracking, motion capture, learning analytics—can reveal how learners allocate attention in AR spaces (Buchner et al., 2021). Combining quantitative measures with qualitative observation and geospatial data logs will enrich interpretation of spatial cognition. Mixed-method triangulation should become standard to capture the interplay of cognition, emotion, and context.

6.3 Teacher-Centric Research

Design-based research involving teachers as co-developers remains scarce. Future work should document how educators adapt AR for curricular coherence and how professional-development experiences reshape their technological-pedagogical reasoning (Mishra, 2019). Exploring teacher identity in relation to digital geography can extend the concept of technological pedagogical content knowledge (TPACK) into spatial domains.

6.4 Ethical and Sustainability Frameworks

Ethical literacy must accompany technological fluency. Researchers should address data privacy, geolocation ethics, and algorithmic bias in AR applications. Moreover, sustainability narratives embedded in AR could help learners envision alternative futures, linking spatial understanding with action competence. Interdisciplinary collaboration between geographers, computer scientists, and ethicists will be vital.

6.5 Toward Inclusive and Accessible AR

Equity considerations demand low-cost, cross-platform solutions. Web-based AR (WebAR) and open-source authoring systems can broaden participation (Beck et al., 2020). Designers should ensure compatibility with assistive technologies and multilingual interfaces to serve diverse learners. Inclusive design also entails recognizing local knowledge and indigenous mapping traditions, aligning with decolonial approaches to geography education.

7. Conclusion

Mobile augmented reality now occupies a pivotal position at the intersection of technological innovation and disciplinary pedagogy. Across the last decade, empirical evidence demonstrates that AR can deepen spatial thinking, enhance motivation, and bridge classroom and field experiences. In geography education, these affordances resonate with the field's epistemic core—understanding the dynamic relationship between space and place.

However, realizing AR's transformative potential requires a shift from sporadic technological experimentation to sustained pedagogical integration. Teachers must become designers of spatial learning experiences, not mere users of apps. Cognitive-load regulation, narrative coherence, and ethical awareness must guide implementation. When these dimensions converge, AR becomes more than a visualization aid: it evolves into a framework for cultivating digital spatial citizenship and sustainable thinking.

Future research should consolidate methodological rigor, promote inclusivity, and strengthen the civic orientation of AR-mediated learning. In doing so, geography education can lead the educational landscape in demonstrating how immersive technologies empower learners to see, think, and act spatially in an increasingly augmented world.

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