



Research Article

Exploring Teachers' Perceptions, Experiences and Needs for Augmented Reality-Based Mathematics Learning in Elementary Schools

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ABSTRACT

Augmented reality (AR) offers promising representational affordances for elementary mathematics, yet its classroom feasibility depends on teachers' experience, technological conditions, and implementation support. This study examined teachers' perceptions of AR, prior digital and AR experience, perceived barriers, mathematics-topic priorities, and requirements for prospective AR-based learning media. A quantitative cross-sectional survey was conducted with 50 elementary-school teachers recruited purposively from 20 public and private schools. Data were collected using a questionnaire assessed for content validity and internal consistency ($S-CVI/Ave = 0.93$; Cronbach's $\alpha = 0.79-0.84$ for multi-item constructs) and analyzed using descriptive statistics and exploratory nonparametric tests with Holm adjustment. Teachers reported highly favorable perceptions across the four measured constructs ($M = 4.59-4.75$), although 62% had no prior AR experience and only 8% used AR often or very often. Three-dimensional geometry received the highest perceived need for AR visualization ($M = 3.30$, $SD = 0.91$). The most prominent barriers were limited technological devices and school infrastructure (both $M = 4.00$), while interactive content, ease of use, offline functionality, curriculum alignment, age-appropriate design, institutional support, and training emerged as key implementation requirements. Exploratory associations involving digital-technology use, prior AR experience, and perception scores did not remain statistically significant after Holm correction. These findings position AR adoption as a teacher-informed, needs-driven design problem and provide an empirical basis for prototype development, usability testing, and classroom feasibility evaluation rather than evidence of AR effectiveness or demonstrated implementation readiness.

KEYWORDS digital learning media • digital pedagogy • elementary education • instructional design • teachers' perceptions • technology integration

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1. INTRODUCTION

Digital transformation has broadened the technological repertoire available for mathematics teaching and learning. However, the educational significance of emerging technologies depends on the representational and pedagogical functions they serve rather than on technological novelty alone. Augmented Reality (AR) is distinguished by its capacity to superimpose digital objects or information onto the physical environment while maintaining real-time interaction between virtual and real-world elements [1], [2]. In educational settings, this capacity allows digital representations to be situated within learners' immediate physical contexts and manipulated through increasingly accessible mobile devices. The growing use of smartphones and tablets has reduced some of the technical barriers that historically restricted AR deployment, although classroom feasibility remains contingent on device compatibility, connectivity, usability, and instructional organization [3], [4]. Research on technology use in mathematics education similarly indicates that the availability of digital tools does not, by itself, ensure meaningful integration; instructional value emerges from the relationship among technology, mathematical content, pedagogical design, and the conditions in which teachers use the technology [5].

AR is particularly relevant to mathematics because mathematical understanding frequently requires coordination among symbolic, graphical, concrete, and spatial representations. This representational demand is pronounced in geometry, measurement, spatial reasoning, and other topics in which learners must mentally construct, rotate, compare, or transform objects that are difficult to communicate fully through static two-dimensional illustrations. Systematic evidence suggests that geometry has become one of the most prominent domains of AR-supported mathematics instruction, partly because interactive three-dimensional representations permit mathematical objects to be viewed and manipulated from multiple perspectives [6], [7]. Recent primary-school studies provide empirical support for this potential. An AR mobile learning system implemented with fifth-grade students was associated with improved achievement among low- and moderate-achieving learners and lower cognitive load compared with conventional materials [8]. However, motivation did not differ significantly between conditions. Second-grade pupils who learned geometry using an AR application demonstrated higher spatial-visualization performance than those who received conventional instruction [9]. These findings indicate that AR may be particularly useful where mathematical learning depends on spatial inspection and manipulation. However, they do not establish that AR is uniformly advantageous across mathematics topics or instructional contexts.

The broader evidence base also supports a cautious rather than technologically deterministic interpretation of AR effectiveness. Garzón and Acevedo's [10] meta-

analysis of 64 quantitative studies identified an overall medium effect of AR on learning gains, learning gains, while a systematic review and meta-analysis of K-12 AR research reported a large aggregated effect [4]. A later meta-analysis covering more than 250 education and training studies found that AR-supported conditions produced learning outcomes approximately three-fifths of a standard deviation above comparison conditions on average [11]. These aggregate effects, however, conceal considerable variation in instructional design, learner characteristics, hardware, learning environment, and outcome measurement. The effectiveness of AR interventions has been shown to vary according to the pedagogical approach used, indicating that AR should not be regarded as an inherently effective instructional technology [12]. Its educational contribution depends on how specific technological affordances are aligned with learning objectives, representational demands, teaching strategies, and classroom interaction.

Despite growing evidence, AR research in mathematics and K-12 education remains largely student-centered. Educational AR studies commonly assess achievement, conceptual understanding, motivation, engagement, spatial ability, and cognitive load [13], [14]. Similar patterns are reported in STEM and mathematics research [15], leaving teacher experience, implementation barriers, content priorities, and media requirements comparatively less integrated. This orientation is valuable for evaluating whether particular AR interventions are associated with desirable learning outcomes, but it offers less information about the conditions that precede implementation. Evidence that students can benefit from a well-designed AR intervention cannot be assumed to indicate that teachers possess sufficient AR-specific experience, that schools provide the required technological infrastructure, or that available AR applications correspond to curriculum priorities and ordinary classroom constraints. Intervention effectiveness and implementation feasibility therefore represent related but analytically distinct questions.

The teacher perspective is central to this distinction. Technology acceptance research identifies perceived usefulness and perceived ease of use as important determinants of users' willingness to accept a technological system [16], while the Technological Pedagogical Content Knowledge framework emphasizes that educational technology integration requires coordinated technological, pedagogical, and content knowledge rather than technical proficiency in isolation [17]. This distinction is especially consequential in primary mathematics. A recent systematic review of TPACK research in primary mathematics education shows that meaningful digital integration is shaped by the interaction of teachers' mathematical knowledge, pedagogical judgment, technological knowledge, professional development, and contextual conditions [18]. Applied to AR, these perspectives suggest that favorable

perceptions of technological usefulness should not be conflated with competence, practical experience, or readiness for classroom implementation. A teacher may consider AR pedagogically promising while having limited experience selecting appropriate applications, organizing AR-supported mathematical activities, evaluating the mathematical accuracy of virtual representations, or managing students' interaction with digital devices.

Recent teacher-focused AR research supports a clear distinction between positive appraisal and practical capability. Educators recognized the pedagogical value of AR but also reported constraints related to digital skills, infrastructure, cost, classroom management, and professional development [19]. The validated TARC framework further conceptualizes AR competence through teachers' capacities to create, use, and manage AR resources [3]. Educators generally expressed positive attitudes toward AR, but their confidence in implementing it was substantially lower, with competence differing according to digital skills and prior classroom experience [20]. Similar discrepancies between perceived pedagogical potential and technological capability have also been reported [21]. Subject-specific research also indicates that purposeful AR integration requires pedagogical and disciplinary competence beyond technical operation [22]. Collectively, these findings justify treating acceptance, experience, competence, professional support, and implementation context as analytically distinct dimensions.

The distinction between general digital-technology experience and AR-specific experience is important in elementary education. Routine use of presentation software, learning platforms, videos, or digital worksheets does not necessarily develop the competencies required to create, manage, and pedagogically integrate AR resources. Among 428 Indonesian elementary-school teachers, digital competence was associated with AR-media skills [23]. Limited teacher competence, instructional-design difficulties, time constraints, and insufficient resources have also been identified as persistent barriers to AR use among primary-school teachers [24]. Internationally, educators generally reported positive attitudes toward AR but lower confidence in creating, using, and managing AR resources, with competence varying according to general digital skills and prior classroom use [3]. Comparable evidence highlights technical, pedagogical, infrastructural, and self-efficacy constraints [19], [21], [25]. General digital experience may therefore facilitate AR adoption but cannot substitute for AR-specific competence, experience, and contextual support.

Implementation also depends on conditions located beyond the individual teacher. Systematic reviews have identified technical difficulties, usability constraints, hardware requirements, and insufficient instructional resources among recurring challenges in educational AR [13]. Teacher-based evidence indicates that AR adoption

depends on pedagogical, technological, and organizational conditions rather than device availability alone. In K-5 contexts, pedagogy, content quality, usability, curriculum alignment, teacher training, and resource availability have been identified as key implementation factors [26]. Large-scale school evidence further identifies limited awareness, infrastructure, funding, and administrative support as barriers [27], while K-12 teachers report curriculum-alignment, technical-support, and classroom-management challenges [28]. Facilitating conditions also shape teachers' intention to adopt immersive AR technologies [29].

This implementation perspective supports needs assessment before AR media are developed or scaled. AR research remains predominantly student-centered, with limited attention to co-design and authentic classroom conditions [30]. Classroom studies show that teacher involvement is essential for identifying pedagogical, usability, and contextual constraints [31], [32]. Teachers' adoption is also influenced by perceived usefulness and facilitating conditions, including time, resources, knowledge, and institutional support [33]. In primary mathematics, needs assessment should therefore identify topic suitability, curriculum alignment, usability, age appropriateness, teacher support, device compatibility, and connectivity requirements before AR development begins.

The literature remains only partially integrated. Mathematics-focused AR research largely emphasizes instructional applications and learner outcomes, particularly geometry, visualization, spatial reasoning, motivation, and cognitive performance [34]–[36], while teacher experience, implementation conditions, and media-development needs receive comparatively less integrated attention. Research on technology integration in primary mathematics emphasizes the integration of technological, pedagogical, and content knowledge rather than technological proficiency alone [37], [38], although this literature addresses digital technology broadly rather than AR specifically. Teacher-focused AR studies have examined attitudes, perceived benefits, competence, previous AR use, barriers, and professional-development requirements across educational subjects and levels [19], [21]. Indonesian research has begun to clarify the association between teachers' digital competence and AR-related skills [23]. What remains less frequently examined within a single elementary-mathematics needs assessment is how teachers' general digital-technology experience and AR-specific experience coexist with mathematics-topic priorities, perceived implementation barriers, available technological conditions, and expectations regarding the design of AR-based mathematics media. This gap concerns integration of evidence rather than an absence of previous work on teachers or AR.

The present study addresses this narrower gap by integrating four analytically related dimensions of

prospective AR implementation in elementary mathematics: (1) teachers' general digital-technology use and previous AR experience; (2) mathematics topics considered suitable for AR-supported instruction; (3) perceived implementation barriers and contextual conditions; and (4) instructional and design characteristics expected from AR-based mathematics learning media. This structure distinguishes exposure to general educational technology from direct AR experience and separates perceptions of AR's potential from the infrastructural and pedagogical conditions required for implementation. It also connects technology-related experience with content-specific priorities and media-development requirements, thereby providing a needs-assessment perspective that complements student-centered intervention research.

The scope of the study is intentionally bounded. It does not test whether AR improves students' mathematics achievement, conceptual understanding, motivation, or spatial ability, and it does not treat teacher readiness as a directly measured construct. Rather, the study provides an exploratory profile of teachers' perceptions, reported digital and AR experience, technological conditions, perceived implementation barriers, mathematics-topic priorities, and expected media characteristics. Any associations identified among these variables are interpreted as exploratory rather than causal. The intended contribution is to provide empirical evidence that can inform the subsequent design and evaluation of AR-based mathematics learning media that are pedagogically relevant, aligned with curriculum content, responsive to teachers' instructional requirements, and feasible within the technological conditions of elementary-school classrooms.

The study aims to: (1) describe elementary-school teachers' demographic and technological-context characteristics relevant to prospective AR implementation; (2) examine their perceptions of the potential educational value of AR for mathematics instruction; (3) identify their general digital-technology use and previous AR experience; (4) identify perceived implementation barriers and support needs; (5) determine mathematics topics and media characteristics considered appropriate for AR-supported learning; and (6) explore selected associations between technology-related experience and AR perceptions. The following research questions were formulated:

- RQ1. What demographic and technological-context characteristics of elementary-school teachers are relevant to the prospective implementation of AR in mathematics learning?
- RQ2. What are teachers' perceptions of the use and potential of AR in elementary mathematics learning?
- RQ3. What experiences do teachers have in using digital technology and AR in mathematics instruction?

- RQ4. What barriers and implementation-support needs do teachers perceive regarding the use of AR in elementary mathematics learning?
- RQ5. What features and characteristics do teachers expect from AR-based learning media for elementary mathematics?
- RQ6. Is there an association between teachers' frequency of digital-technology use in mathematics instruction and their previous experience with AR?
- RQ7. Is there a difference in teachers' AR-related perception scores between those with and without previous AR experience?

2. LITERATURE REVIEW

Research on augmented reality (AR) in mathematics education should distinguish technological affordances, teacher readiness, and contextual feasibility. Although reviews generally report benefits for visualization, achievement, and engagement, outcomes vary across learner, technological, and instructional conditions [10], [11], [13], [39]. These benefits do not establish teacher preparedness or adequate institutional support, underscoring the need for teacher-informed needs assessment rather than technology-driven adoption.

2.1. Augmented Reality in Mathematics Learning

Augmented Reality (AR) combines real and virtual content, aligns them in three-dimensional space, and enables real-time interaction [1]. Contemporary AR systems include handheld, projection-based, and head-mounted configurations [40]. In mathematics education, its value lies primarily in coordinating physical action with digital and spatial representations. This capability is particularly relevant when learners interpret spatial relationships, connect symbolic and visual representations, manipulate geometric objects, or observe invariant properties during transformation [41]. AR can therefore make mathematical objects more inspectable through rotation, resizing, decomposition, and multiple perspectives.

However, the instructional value of AR cannot be inferred from three-dimensionality or technological novelty alone. Although augmentation may reduce the need to translate between separate physical and visual representations, it can also introduce visual clutter, unfamiliar interaction procedures, split attention, and cognitive overload. Reviews have consistently identified usability problems, technical instability, and excessive cognitive demands alongside potential gains in visualization and engagement [13], [14]. More recent evidence similarly indicates that cognitive demand depends on spatial placement, interaction, contextual information, guidance, content, and display design [42]. The relevant question is therefore whether augmentation clarifies a mathematical relationship without introducing unnecessary operational or representational demands.

Research on AR in mathematics education has expanded rapidly but remains uneven across topics, populations, and technologies. Reviews have documented growing evidence while identifying persistent limitations in theoretical grounding, evaluation, and sustained classroom implementation [43]. Erşen & Alp [44] found that achievement, attitudes, motivation, and spatial thinking dominated mathematics-focused AR research, with secondary students studied more frequently than primary pupils or teachers. Hidajat [36] similarly reported substantial variation in curriculum applications, learning purposes, technologies, and evaluation approaches. At the broader STEM level, marker-based, marker-less, and projection-based systems remain common, frequently incorporating cameras, object markers, three-dimensional models, and animation [40]. Such heterogeneity limits straightforward generalization across platforms, age groups, and mathematical topics.

Geometry has received particular attention because many geometric and measurement tasks depend on spatial visualization, mental rotation, orientation, and coordination of multiple views [7]. A review of 23 studies indicated that geometry and measurement were particularly prominent in primary and lower-secondary AR research [7]. Although most studies reported beneficial outcomes, the results varied across tools, intervention duration, assessment methods, and learning contexts. Evidence from individual studies further supports this conditional pattern. Mobile AR improved geometry achievement among lower- and medium-achieving fifth-grade students and reduced cognitive load, but did not significantly improve motivation [8]. Other studies likewise reported learning benefits while indicating that outcomes depended on task design, learner experience, and instructional context [45]. Therefore, improvement in one outcome should not be interpreted as evidence of improvement across all learning dimensions or of routine classroom feasibility.

The instructional medium also appears to interact with the mathematical task. In a preregistered experiment, identical geometry simulations were compared across tablet-based and head-mounted AR conditions [46]. AR supported initial understanding of three-dimensional shapes but was less effective for two-dimensional content and provided no advantage for generating mathematical justifications or generalizations. Tablet users manipulated figures more frequently, whereas AR users produced more unconstrained gestures. These findings indicate that content dimensionality, interface affordances, and the form of mathematical reasoning being assessed can modify AR's effectiveness. They also caution against interpreting positive average effects from meta-analyses as evidence that AR is uniformly preferable across learning objectives [47], [48].

Motivational effects require similar caution. Although AR has shown a positive overall association with K-12 motivation, effect sizes vary across intervention and

study characteristics [49]. Initial interest may partly reflect novelty, whereas sustained engagement depends on task quality, usability, feedback, and instructional integration. AR is therefore most defensible when it provides representational value that simpler resources cannot readily offer, particularly by enabling learners to perceive, manipulate, or coordinate mathematical relationships in otherwise difficult ways.

These considerations have direct methodological implications for the present study. Most intervention research evaluates AR after the technology, topic, and instructional design have already been selected. Such studies can estimate learning outcomes under specified conditions but do not determine whether existing applications align with teachers' curriculum priorities, available infrastructure, implementation support, or classroom usability. A teacher-informed needs-assessment approach therefore shifts the focus from whether AR can be effective to which mathematical needs warrant augmentation and what technical, pedagogical, and organizational conditions are required for feasible implementation.

2.2. Teacher Readiness and Pedagogical Capacity

Teachers are central to educational technology adoption because classroom implementation depends on pedagogical judgment as well as technological access. The Technology Acceptance Model (TAM) identifies perceived usefulness and ease of use as key determinants of attitudes and behavioral intentions [16], while the Unified Theory of Acceptance and Use of Technology emphasizes performance expectancy, effort expectancy, social influence, and facilitating conditions [50]. A meta-analysis of 114 studies involving 34,357 teachers confirmed the relevance of these factors while showing substantial variation across technologies and contexts [51]. These models suggest that teachers are more likely to consider AR when they perceive instructional value, manageable demands, and supportive implementation conditions.

Acceptance, however, does not equate to pedagogical capacity. Technology-acceptance models primarily explain teachers' intentions and adoption of digital tools, whereas effective technology integration depends on the coordinated alignment of technological, pedagogical, and content knowledge [31], [52]. For AR-based mathematics instruction, this requires teachers to select representations and interactions that are mathematically meaningful and pedagogically aligned; thus, positive attitudes toward AR may coexist with limited capacity for effective classroom implementation.

Teachers' behavioral intentions to use AR were associated with attitudes, perceived usefulness, and facilitating conditions [33]. Among preservice teachers, educational value, social influence, mobile AR self-efficacy, immersion, and ease of use were also associated with intention to use AR [53]. However, these findings

primarily reflect reported intentions following structured exposure and do not demonstrate sustained classroom use. Research with practicing teachers further illustrates the distinction between favorable perceptions and implementation preparedness.

Educators associated AR with greater engagement, interactivity, and support for representing complex concepts, while also identifying concerns related to infrastructure, applications, digital skills, cost, classroom management, safety, and professional development [19]. Positive perceptions of AR's pedagogical potential were also accompanied by lower perceived technological competence, with more favorable evaluations among teachers who had received AR training or had greater prior experience [21].

The TPACK framework provides a complementary perspective by conceptualizing effective integration as the interaction of technological, pedagogical, and content knowledge [17]. Its enactment is also shaped by resources, learner characteristics, curriculum demands, institutional structures, and professional culture [54]. Research in primary mathematics likewise highlights lesson design, digital integration, assessment, and professional development while identifying continuing weaknesses in contextual integration and TPACK measurement [18].

For AR-based mathematics instruction, operational familiarity is therefore insufficient. Teachers must judge

mathematical validity, determine when augmentation supports conceptual understanding, integrate manipulation with explanation, and manage devices and student interaction. These demands reflect broader evidence that technology integration emerges from interactions among access, beliefs, knowledge, support, and school conditions rather than from any single factor [55], [56].

Teacher readiness should consequently be interpreted cautiously when it is not measured directly. Positive attitudes, general digital-technology use, prior AR exposure, perceived usefulness, and adoption intentions can describe implementation conditions but do not constitute demonstrated competence or actual classroom use. In an exploratory self-report needs assessment, these dimensions should be reported separately, with readiness treated as an interpretive concept rather than a directly measured latent construct.

The literature reviewed above indicates that multiple interrelated dimensions, including representational affordances, teacher perceptions, prior technology experience, implementation barriers, and instructional requirements shape AR implementation in elementary mathematics. Table 1 synthesizes the principal evidence from previous research and identifies the unresolved issues addressed in the present study.

Table 1. Synthesis of Literature Relevant to AR Implementation in Elementary Mathematics

Literature domain	Evidence from previous research	Remaining issue for the present study
AR representational affordances	Supports visualization, interaction, and spatial representation, particularly in geometry	Limited evidence on which mathematics topics teachers themselves prioritize for AR
Teacher perceptions and acceptance	Perceived usefulness, ease of use, and educational value influence adoption intentions	Positive perception does not establish AR-specific experience or readiness
Digital and AR experience	General technology familiarity can support adoption	General digital use and AR-specific experience are rarely distinguished
Implementation barriers	Devices, connectivity, training, cost, and institutional support constrain implementation	Barriers are often examined separately from instructional and media requirements
Pedagogical integration	Effective integration requires technological, pedagogical, and content knowledge	Limited teacher-informed evidence on curriculum alignment and classroom usability
Media requirements	Usability, accessibility, and pedagogical suitability are important	Few studies integrate these requirements within a mathematics-specific needs assessment

2.3. Implementation Contextual and Instructional

AR implementation is shaped by interacting technical, pedagogical, and organizational conditions. Ertmer [57] distinguished between first-order barriers, including equipment, access, time, and support, and second-order barriers, including beliefs, confidence, and established practice; this distinction remains relevant because resolving one category does not automatically address the other. Reviews similarly identify resources, teacher knowledge, institutional arrangements, beliefs, assessment, and subject culture as recurrent determinants of technology integration [55], [56]. Implementation feasibility therefore cannot be inferred

from a single indicator such as internet availability or teacher interest.

AR introduces additional technical and instructional demands. Device compatibility, processing capacity, connectivity, application stability, privacy, and maintenance affect reliability. At the same time, teachers must ensure content accuracy, curriculum alignment, appropriate guidance, attention management, and integration of manipulation with mathematical explanation. Organizational requirements may include procurement, scheduling, technical assistance, professional learning, and preparation time. Teacher studies consistently identify cost, insufficient equipment, limited educational applications, uneven digital

competence, classroom-management concerns, and inadequate institutional support as barriers [19], [21].

These considerations are particularly important in elementary mathematics. Younger learners may require simpler interfaces, explicit guidance, shorter interaction sequences, and closer teacher mediation. A technically functional application may still be developmentally inappropriate, poorly aligned with the curriculum, or unnecessarily complex. Evidence on cognitive load indicates that augmentation can support learning when relevant information is spatially integrated, but redundant or distracting elements can impose additional demands [14], [42]. Usability, accessibility, guidance, and age appropriateness are therefore components of instructional quality.

Implementation analysis should also distinguish school-level infrastructure from classroom-level access. General connectivity does not guarantee sufficient devices, charging facilities, compatible systems, bandwidth, or equitable student access. Similarly, teacher smartphone ownership does not establish whether student device use is permitted or manageable. Facilitating conditions refer more broadly to the organizational and technical resources that enable use [33], [50]. Needs assessment should therefore consider device availability, connectivity, technical assistance, policy, preparation time, student access, and opportunities for teachers to experiment with AR as related but distinct conditions.

Content selection should likewise precede technology selection. The concentration of AR research in geometry, measurement, and spatial reasoning suggests particular relevance where learners must understand orientation, transformation, cross-sections, multiple views, or three-dimensional relationships [7], [44]. This does not mean that every geometric topic requires AR or

that other domains are unsuitable. Studies have also addressed algebra, functions, probability, and mathematical modeling [36], [40]. The instructional justification should instead be whether augmentation addresses a representational or interaction problem more effectively than simpler media [46]. For example, benefits found for initial three-dimensional understanding did not extend to two-dimensional content or higher-order justification.

The same principle applies to AR-media design. Educational outcomes depend partly on instructional design and pedagogical approach rather than on the technology alone [12], [39]. Teacher-informed development should therefore identify requirements such as ease of operation, mathematically accurate and manipulable representations, curriculum alignment, age-appropriate instructions, purposeful interaction, feedback, accessibility under limited connectivity, and teacher control. Offline functionality or lightweight mobile deployment may be more relevant in some settings than technologically sophisticated but resource-intensive systems.

The resulting research gap extends beyond whether AR is effective or accepted. Existing research has examined student outcomes, spatial visualization, technology acceptance, teacher perceptions, cognitive load, and implementation barriers, but these dimensions are often studied separately. Primary pupils and teachers also remain less represented than secondary learners, while contextual and process variables are inconsistently reported [44]. Less is known about how elementary mathematics teachers' digital and AR experience, perceived topic needs, anticipated barriers, implementation support, and desired media characteristics converge within a single needs-assessment framework.

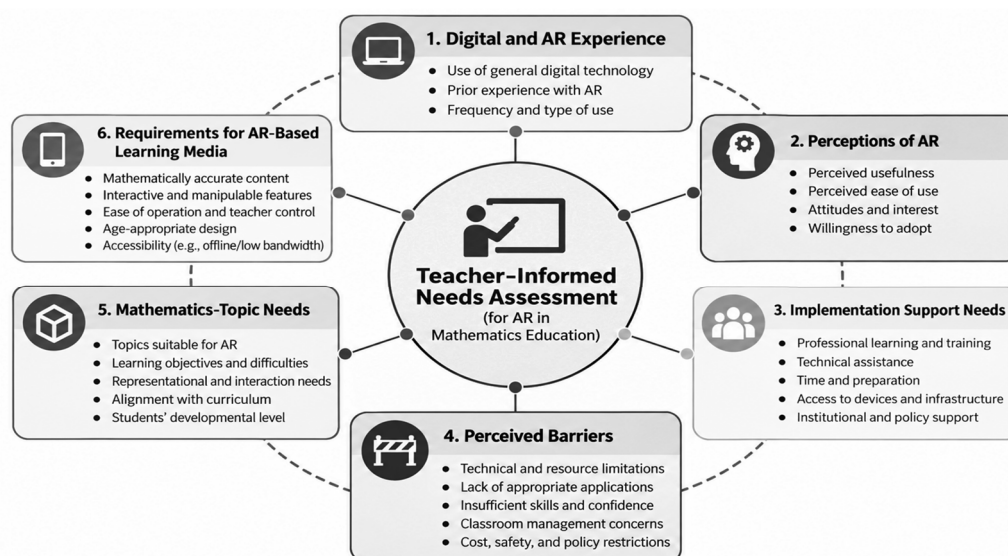


Figure 1. Teacher-informed needs assessment framework for augmented reality in mathematics education.

Figure 1 summarizes the conceptual organization of the study by positioning six domains as complementary components of a teacher-informed needs assessment. The framework is intended to guide the empirical description of teachers' experiences, perceptions, support needs, perceived barriers, mathematics-topic priorities, and requirements for AR-based learning media, rather than to specify causal pathways among these domains. Accordingly, no directional, predictive, or latent-variable relationships are assumed. Teacher readiness is retained as an interpretive concept derived from prior literature, but it is not operationalized as a directly measured construct in the present study. Instead, readiness is inferred cautiously from the pattern of descriptive evidence across the assessed domains. This distinction is important for maintaining consistency between the conceptual framework, questionnaire structure, exploratory research design, and the level of inference supported by the data.

3. MATERIALS AND METHODS

3.1. Research Approach

This study employed a quantitative cross-sectional survey design to investigate elementary school teachers' perceptions, experiences, technological conditions, perceived barriers, and instructional needs related to prospective AR implementation in mathematics learning. Cross-sectional designs are appropriate for characterizing conditions and perceptions within a defined period, although simultaneous measurement constrains

temporal ordering and causal inference [58]. Accordingly, the study emphasized description and limited exploratory comparison rather than causal explanation.

The descriptive component summarized demographic characteristics, technological facilities, digital-technology and AR experience, perceived barriers, instructional needs, and perception scores using frequencies, percentages, means, and standard deviations, consistent with established approaches to summarizing categorical and continuous data [59]. These analyses were intended to characterize the participating teachers and their reported implementation context rather than generate population-level estimates.

Exploratory inferential analyses examined selected patterns beyond the descriptive results. The association between five-level digital-technology use and prior AR experience was examined using the Fisher-Freeman-Halton exact test, an extension of Fisher's exact procedure for $(r \times c)$ contingency tables that is appropriate when small samples or sparse cells make asymptotic approximations less reliable [60]. Perception scores for teachers with and without prior AR experience were compared using the Mann-Whitney U-test, whereas differences across levels of digital-technology use were explored using the Kruskal-Wallis test. These rank-based nonparametric procedures are appropriate alternatives when parametric assumptions are not adequately supported [61]. Effect sizes were reported alongside p -values to provide information about the magnitude of observed associations or differences rather than relying solely on statistical significance [62]. The overall research procedure is presented in Figure 2.

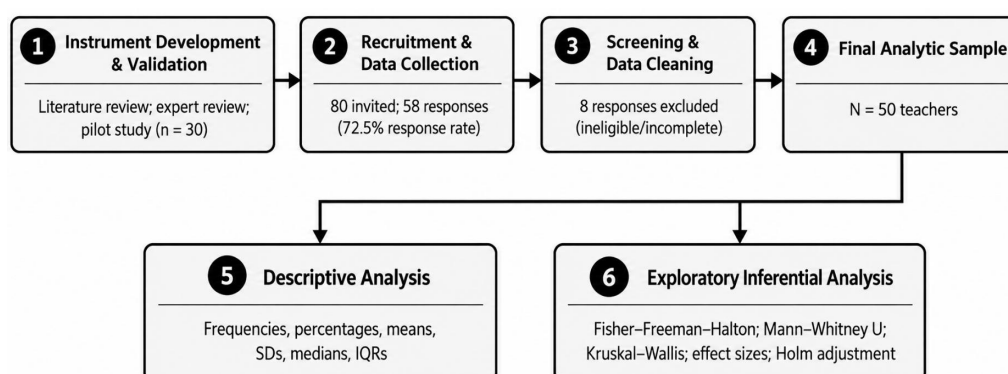


Figure 2. Study workflow from instrument development and participant recruitment to data screening and statistical analysis.

Given the purposive and relatively small sample, inferential analyses were treated as exploratory and subordinate to the descriptive needs-assessment purpose. Purposive sampling constrains population-level generalizability because participants are selected according to study-specific criteria rather than through probability-based procedures [63]; therefore, no association was interpreted causally or generalized beyond the study context [58], [64].

3.2. Participants, Data Collection and Sampling

The target population comprised elementary school teachers responsible for mathematics instruction in public and private schools. Purposive sampling was used because participants were selected based on characteristics directly relevant to the study purpose, particularly their active involvement in elementary mathematics teaching. Although appropriate for targeted recruitment, this nonprobability approach limits population-level generalization [64]. Participants were

recruited through school coordination networks, professional teacher groups, and teacher associations in West Java and other participating regions.

Eligibility criteria required participants to be currently employed as elementary school teachers, actively teaching mathematics, willing to provide informed consent, and able to complete the online questionnaire. Previous experience with digital learning technologies was not required because technology use was examined as a study variable. Teachers who did not meet the eligibility criteria or submitted incomplete questionnaires were excluded. Explicit reporting of eligibility and recruitment procedures supports transparency and assessment of sample applicability [65].

Table 2. Participant Recruitment and Screening

Recruitment stage	N	%
Teachers invited	80	100.0
Questionnaires submitted	58	72.5 ¹
Questionnaires excluded after screening	8	13.8 ²
Final analytic sample	50	62.5 ¹
Valid questionnaires among submissions	50	86.2 ²

Note. ¹Percentage of invited teachers (n = 80). ²Percentage of submitted questionnaires (n = 58).

Data were collected during March–April 2026 using a structured questionnaire administered through Google Forms, with recruitment procedures reported in accordance with recommendations for online survey research [66]. Transparent reporting of participant disposition facilitates evaluation of potential nonresponse and selection effects [67].

The final analytic sample comprised 50 teachers from 20 elementary schools, including 14 public and 6

private schools (Table 2). Participants were drawn from Tasikmalaya City (40%, n = 20), Tasikmalaya Regency (30%, n = 15), Ciamis Regency (20%, n = 10), and other regions, including Jambi Province (10%, n = 5). Sample size was determined pragmatically in accordance with the exploratory needs-assessment objective rather than through an a priori power calculation; consequently, inferential analyses were treated as exploratory, and no population-level representativeness was assumed [68].

3.3. Research Instrument

3.3.1. Instrument Structure

The first section comprised 18 five-point Likert-scale items (1 = strongly disagree to 5 = strongly agree) organized into four multi-item constructs: contextual mathematics learning needs (6 items), technology support and implementation needs for mathematics learning (6 items), perceived potential of AR in mathematics learning (3 items), and perceived need and interest in AR adoption (3 items). Construct scores were calculated as the mean of the corresponding items, with higher scores indicating stronger perceptions or perceived needs.

The remaining sections assessed digital technology and AR experience, technological facilities, mathematics topics requiring AR visualization, implementation barriers, and instructional and media requirements. These sections were analyzed at the item or category level because their items represented distinct experiences, resources, topics, constraints, or implementation requirements rather than indicators of a single homogeneous construct. The structure, response format, and scoring procedures are in Table 3.

Table 3. Structure and scoring of the research instrument.

Sec.	Domain/construct	Items	Response format	Analysis
1	AR perceptions: contextual mathematics needs; technology support and implementation needs; perceived AR potential; need and interest in AR adoption	18 (6, 6, 3, 3)	5-point Likert	Construct mean
2	Digital technology and AR experience	3	Categorical	n, %
3	Technological facilities	9	Multiple response	n, %
4	Mathematics topics requiring AR visualization	5	5-point rating	Item mean, SD
5	Perceived AR implementation barriers	8	5-point rating	Item mean, SD
6	Instructional and media requirements	8	5-point rating	Item mean, SD

3.3.2. Content Validation and Pilot Testing

The questionnaire items were adapted from previous studies on technology acceptance, digital learning media, and AR integration in education through indicator identification, contextual modification, and review for conceptual alignment and clarity, consistent with established instrument-development procedures [69].

Content validity was independently evaluated by three experts in educational technology, elementary mathematics education, and educational measurement, who assessed item relevance, clarity, construct alignment, and contextual appropriateness on a five-point scale. Ratings of 4 or 5 were classified as relevant, and the item-level Content Validity Index (I-CVI) was calculated as the proportion of experts assigning these ratings, consistent

with established CVI procedures [70]. The overall S-CVI/Ave was 0.93. Ten items were revised following expert feedback, primarily for wording, contextual appropriateness, and construct alignment, whereas no items were removed.

Following content validation, the revised questionnaire was pilot-tested with 30 elementary school teachers to assess item clarity and preliminary internal consistency; this sample size is consistent with recommendations for initial survey or scale-development pilot studies [71]. Cronbach's alpha coefficients for the four multi-item perception constructs ranged from 0.79 to 0.84, and corrected item-total correlations were examined for the corresponding items. Reliability analysis was not applied to categorical, multiple-response, topic-specific, barrier, or instructional-requirement items because these were treated as distinct descriptive indicators rather than homogeneous scales.

3.4. Data Analysis

Data were analyzed using IBM SPSS Statistics version 25. Prior to analysis, responses were screened for duplication, incompleteness, missing data, and invalid entries. Categorical variables were numerically coded, while five-point rating responses were scored according to their respective anchors. Mean composite scores were calculated for the four multi-item perception constructs. Descriptive statistics included frequencies and percentages for categorical variables and means and standard deviations for rating-scale items and composite scores, consistent with established approaches to summarizing survey and rating-scale data [59], [72]. Mean scores were interpreted using predetermined equal-width intervals of 0.80: (1.00–1.80 = very low/not needed at all), (1.81–2.60 = low), (2.61–3.40 = moderate), (3.41–4.20 = high) and (4.21–5.00 = very high), with labels adapted to the construct being measured.

Exploratory inferential analyses examined selected technology-related patterns. The association between five-level digital-technology use and prior AR experience

was tested using the Fisher–Freeman–Halton exact test, an extension of Fisher's exact test for larger contingency tables [73]. Perception scores were compared between teachers with and without prior AR experience using the Mann–Whitney U test, while differences across digital-technology-use levels were examined using the Kruskal–Wallis test [61]. Effect sizes were reported as Cramér's V, r , and epsilon-squared (ϵ^2), respectively, because effect-size estimates complement p-values by indicating the magnitude of observed effects [62]. To account for the three exploratory comparisons, Holm's sequentially rejective procedure was applied to control the family-wise error rate [74]. Statistical significance was set at $\alpha = 0.05$, and both unadjusted and Holm-adjusted p-values were reported.

4. RESULTS

4.1. Teacher Characteristics and Technological Setting

The study included 50 elementary school teachers, with the sample concentrated in Tasikmalaya City and Tasikmalaya Regency, which together accounted for 35 respondents (70%). The remaining participants were from Ciamis Regency and other regions. Teaching experience varied across the sample: the largest categories were less than five years and 11–20 years, each comprising 17 teachers (34%), followed by 5–10 years and more than 20 years (Table 4). Participants taught across Grades I–VI, with Grade VI most frequently represented (13 teachers, 26%), followed by Grade IV (10 teachers, 20%) and Grade V (9 teachers, 18%).

All respondents rated their internet availability as either very good (35 teachers, 70%) or adequate (15 teachers, 30%); none reported limited or unavailable access. These ratings describe perceived internet availability and are considered separately from the availability of specific technological resources and the difficulties associated with implementing augmented reality (AR) in classroom instruction.

Table 4. Selected teacher characteristics and self-reported internet availability.

Characteristic	Category	Participant (n=50)	Percentage (%)
Region	Tasikmalaya City	20	40
	Tasikmalaya Regency	15	30
	Ciamis Regency	10	20
	Other regions	5	10
Teaching experience	< 5 years	17	34
	5–10 years	9	18
	11–20 years	17	34
	> 20 years	7	14
Self-reported internet availability	Very good	35	70
	Adequate	15	30
	Limited or unavailable	0	0

Table 5. Technological resources reported as available by participating teachers.

Technological resource	Teachers reporting availability (n=50)	Percentage (%)
Wi-Fi	49	98
Projector	47	94
Laptop	44	88
LCD display	28	56
Students' smartphones	8	16
Tablet	6	12
Interactive flat panel	2	4
Digital interactive board	2	4
Other digital facilities ^a	1-2	2-4

Reported technological resources showed a marked contrast between commonly available connectivity and computing resources and less frequently reported handheld devices and interactive displays (Table 5). Wi-Fi, projectors, and laptops were each reported at least 88% of respondents, whereas LCD displays were reported by 56%. Students' smartphones and tablets were reported by considerably smaller proportions of teachers, at 16% and 12%, respectively. Interactive flat panels and digital interactive boards were each reported by 4%. Thus, the resource profile was not uniformly extensive across technology categories, despite favorable overall ratings of internet availability.

4.2. Perceived Need and Potential of AR in Mathematics Learning

Four perception constructs addressed contextual mathematics learning needs, technology support and implementation needs, perceived AR potential, and need

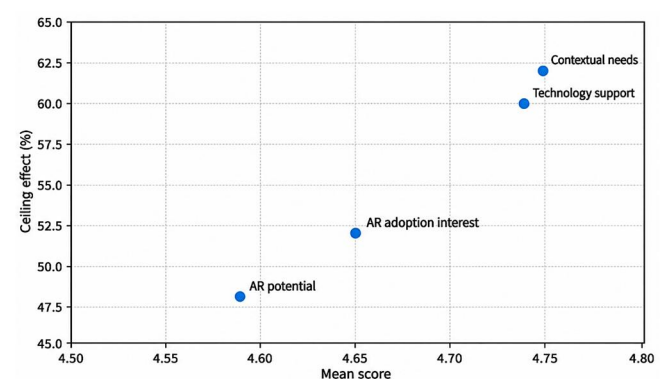
and interest in AR adoption. Fifty teachers responded to 18 five-point Likert items. Scores describe perceived instructional needs and expectations; they do not directly measure AR competence, implementation readiness, or effects on learning.

Responses clustered at the upper end of all four scales (Table 6). Construct means ranged from 4.59 to 4.75, and each median was 5.00. Contextual mathematics learning needs ($M = 4.75$, $SD = 0.49$) and technology support and implementation needs ($M = 4.74$, $SD = 0.53$) were closely rated. Perceived need and interest in AR adoption ($M = 4.65$, $SD = 0.55$) and perceived AR potential ($M = 4.59$, $SD = 0.55$) were also high. The interquartile range was 0.00 for the first two constructs and 1.00 for the AR-specific constructs. Ceiling proportions ranged from 48% to 62%, indicating restricted variation at the upper end of the scales. Figure 3 displays the means and ceiling proportions; the descriptive differences do not establish differences among constructs.

Table 6. Construct-Level Descriptive Statistics for Teachers' Perceptions of AR-Supported Mathematics Learning (N = 50)

Construct	Items	M	SD	Approx. 95% CI	Median	IQR	Ceiling (%)
Contextual Mathematics Learning Needs	6	4.75	0.49	4.61 – 4.89	5.00	0.00	62.0
Technology Support and Implementation Needs	6	4.74	0.53	4.59 – 4.89	5.00	0.00	60.0
Perceived Potential of AR in Mathematics Learning	3	4.59	0.55	4.43 – 4.75	5.00	1.00	48.0
Perceived Need and Interest in AR Adoption	3	4.65	0.55	4.49 – 4.81	5.00	1.00	52.0

At the item level, the strong endorsement of contextualized mathematics instruction was particularly consistent. Eighty-six percent of teachers selected strongly agree for statements indicating that mathematics should be presented more concretely and contextually, that mathematical concepts are easier to understand when connected to everyday life, and that innovative learning media are needed in mathematics instruction. A further 80% strongly agreed that supportive learning media are required to strengthen students' numeracy skills. These responses indicate that the perceived need for innovation was rooted primarily in teachers' views of mathematics pedagogy rather than in technology adoption alone.

**Figure 3.** Mean scores and corresponding ceiling effects across the four study constructs.

Teachers also expressed favorable expectations regarding the instructional potential of AR. For the item concerning the visualization of abstract mathematical concepts, 58% strongly agreed and 40% agreed; corresponding proportions were 56% and 42% for supporting the understanding of mathematical concepts, and 58% and 40% for increasing students' attention and curiosity. Consequently, approximately 98% of respondents selected either agree or strongly agree across these three indicators. These findings indicate a strong perceived affordance of AR for representation and engagement. They should, however, be interpreted as teachers' expectations about prospective instructional benefits rather than as evidence that AR had already improved students' conceptual understanding, attention, or academic achievement.

Adoption-related items also specified conditions teachers considered appropriate for elementary education. Seventy-four percent strongly agreed that AR media should be simple, safe, and age-appropriate; 64% strongly expressed interest in using AR for mathematics. Another 58% strongly agreed and 38% agreed that AR-based media represented an educational need. The construct thus combines perceived demand and

prospective interest, without directly measuring confidence, proficiency, or independent implementation capacity.

Across the four constructs, teachers endorsed contextual mathematics instruction, supporting technology conditions, and potential AR applications. The responses identify design considerations, including usability, age appropriateness, infrastructure, training, and operation under limited connectivity. They provide a basis for prototype and feasibility work, but do not demonstrate AR effectiveness or teacher readiness.

4.3. Digital-Technology Use and AR Experience

Table 7 summarizes teachers' self-reported use of digital technology in mathematics instruction, previous experience with Augmented Reality (AR), and frequency of AR use. These indicators were examined separately because general familiarity with digital technology does not necessarily represent AR-specific experience. Accordingly, the results in this section describe teachers' reported exposure to technology rather than their technological competence or implementation readiness.

Table 7. Teachers' Digital-Technology Use and Prior Experience with Augmented Reality in Mathematics Learning (n=50).

Experience	Category	Frequency (n)	Percentage (%)
Digital technology use	Very low	1	2.0
	Low	5	10.0
	Moderate	14	28.0
	High	20	40.0
	Very high	10	20.0
Prior AR experience	Yes	19	38.0
	No	31	62.0
Frequency of AR use	Never	31	62.0
	Rarely	9	18.0
	Sometimes	6	12.0
	Often	3	6.0
	Very often	1	2.0

General digital-technology use was concentrated toward the upper end of the response categories. Thirty teachers (60.0%) reported high or very high use of digital technology in mathematics instruction, while another 14 teachers (28.0%) reported moderate use. Only six participants (12.0%) reported low or very low use. Thus, 88.0% of the sample reported at least moderate use of digital technology, indicating that digital tools were relatively common within the instructional experience of the participating teachers.

AR-specific experience showed a substantially different descriptive pattern. Only 19 teachers (38.0%) reported any previous experience with AR, whereas 31 (62.0%) reported no prior experience. Consistent with this limited exposure, 31 teachers (62.0%) reported never

using AR, 9 (18.0%) used it rarely, 6 (12.0%) sometimes, 3 (6.0%) often, and only 1 teacher (2.0%) very often. Among the 19 respondents reporting a frequency above "never," nearly half were in the rarely category (47.4%), followed by sometimes (31.6%), often (15.8%), and very often (5.3%). AR exposure among users was therefore predominantly occasional rather than routine.

Although 60% of teachers reported high or very high use of general digital technologies, only 38% had prior AR experience and 8% reported using AR often or very often. General digital familiarity therefore should not be interpreted as equivalent to AR-specific experience. This limited exposure suggests that targeted training and implementation support may be relevant when introducing AR-based mathematics learning

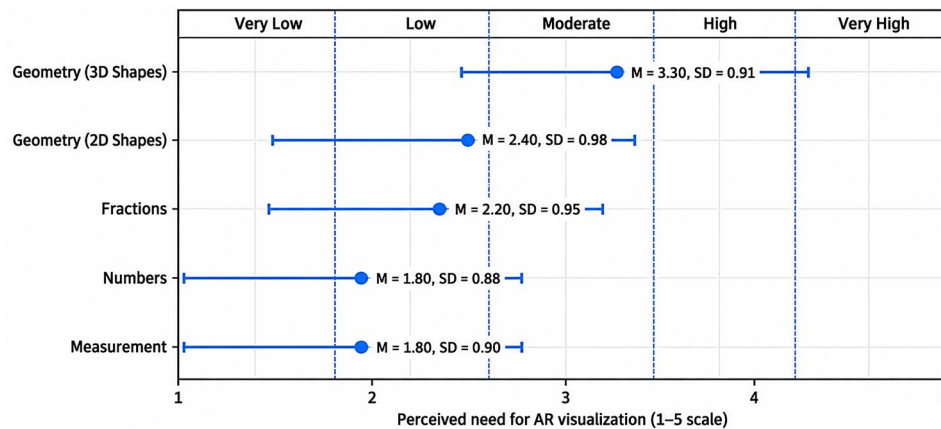


Figure 4. Perceived need for AR-based visualization across elementary mathematics topics.

Figure 4 summarizes teachers' perceived need for AR across selected mathematics topics. Mean scores were derived directly from five-point Likert responses. Points indicate mean ratings, error bars show standard deviations, and dashed lines mark the predefined interpretation categories from Very Low to Very High. Among the five topics, Geometry (3D Shapes) obtained the highest mean score ($M = 3.30$, $SD = 0.91$), which falls within the moderate-need category. This finding indicates that teachers perceived three-dimensional geometry as the mathematics topic with the greatest need for AR-based visualization support among the topics examined. Geometry (2D Shapes) received a mean score of 2.40 ($SD = 0.98$), while Fractions obtained a mean score of 2.20 ($SD = 0.95$). Both were classified as low need, indicating relatively lower perceived needs for AR-based visualization support compared with three-dimensional

geometry. Meanwhile, Numbers and Measurement each obtained a mean score of 1.80, with standard deviations of 0.88 and 0.90, respectively. Based on the predetermined interpretation intervals, both topics fall within the not-needed-at-all category.

4.4. Mathematics Topics for AR Visualization

Despite teachers' generally positive perceptions of AR, several implementation constraints were identified. These barriers relate to technological resources, infrastructure, teacher capacity, student access, connectivity, and classroom integration. Table 8 summarizes the perceived severity of each barrier based on mean scores, standard deviations, and the proportion of respondents rating each barrier as high or very high.

Table 8. Barriers to Implementing Augmented Reality (AR) in Elementary Mathematics Learning Identified by Teachers ($n=50$)

Perceived Barrier	Mean (M)	SD	Percentage (%)	Interpretation
Limited technological devices in schools	4.00	0.78	80.0	High
Limited school infrastructure support	4.00	0.76	80.0	High
Limited teacher competence in AR utilization	3.70	0.84	74.0	High
Lack of training related to AR integration	3.70	0.82	74.0	High
Limited student access to digital devices	3.60	0.85	72.0	High
Limited availability of AR-based learning media	3.50	0.87	70.0	High
Inadequate internet connectivity in certain areas	3.40	0.89	68.0	Moderate
Difficulty integrating AR into classroom instruction	3.20	0.91	64.0	Moderate

Note. Items were rated on a five-point scale ranging (1 = Very Low Barrier to 5 = Very High Barrier). The percentage column represents respondents rating each item (High or Very High Barrier). Mean-score interpretations were based on the predefined intervals (1.00–1.80 = Very Low, 1.81–2.60 = Low, 2.61–3.40 = Moderate, 3.41–4.20 = High, and 4.21–5.00 = Very High).

Table 8 summarizes teachers perceived barriers to implementing Augmented Reality (AR) in elementary mathematics learning. The most prominent barriers were limited technological devices in schools and limited school infrastructure support (both $M = 4.00$), with 80% of respondents rating these as high or very high barriers. Teacher-related constraints were also substantial, including limited competence in AR utilization and lack of

AR-integration training (both $M = 3.70$; 74%), followed by limited student access to digital devices ($M = 3.60$; 72%).

High barriers included the limited availability of AR-based learning media ($M = 3.50$), inadequate internet connectivity ($M = 3.40$), and difficulty integrating AR into classroom instruction ($M = 3.20$). The pattern indicates that the main constraints are concentrated in infrastructure, device access, and teacher capacity, rather than instructional integration alone. These findings

highlight the need for AR implementation strategies that combine adequate technological resources, accessible student devices, teacher training, and context-sensitive learning media.

4.5. Teachers Needs for AR-Based Learning Media

Teachers identified several requirements for AR-based mathematics learning media, covering usability,

accessibility, pedagogical alignment, content design, teacher support, and institutional conditions. These requirements were assessed independently to determine which features and implementation supports teachers considered most important for prospective AR use in elementary mathematics. Table 9 presents the mean scores, standard deviations, and interpretation of each identified need.

Table 9. Teachers' Requirements for AR-Based Mathematics Learning Media (n=50).

Rank	Teachers' Requirements	Mean (M)	Std Dev (SD)	Interpretation
1	Interactive and engaging AR content	4.20	0.70	High
2	Easy-to-use AR learning media	4.10	0.74	High
3	AR applications that function offline	4.00	0.77	High
3	Institutional support for technology integration	4.00	0.79	High
5	AR media aligned with curriculum objectives	3.90	0.81	High
6	Simple and age-appropriate AR design	3.80	0.85	High
7	Teacher training on AR integration	3.70	0.88	High
8	AR media for visualizing abstract mathematical concepts	3.10	0.92	Moderate

Note. Items were rated on a five-point scale (1 = Not Needed at All to 5 = Very Highly Needed). Mean scores were interpreted using intervals (1.00–1.80 = Very Low/Not Needed at All, 1.81–2.60 = Low, 2.61–3.40 = Moderate, 3.41–4.20 = High, and 4.21–5.00 = Very High).

Table 9 shows that most requirements were rated at a high level of need. Interactive and engaging AR content received the highest mean score ($M = 4.20$, $SD = 0.70$), followed by easy-to-use AR learning media ($M = 4.10$, $SD = 0.74$). Teachers also reported high needs for offline functionality ($M = 4.00$, $SD = 0.77$) and institutional support for technology integration ($M = 4.00$, $SD = 0.79$). Curriculum alignment ($M = 3.90$, $SD = 0.81$), simple and age-appropriate design ($M = 3.80$, $SD = 0.85$), and teacher training in AR integration ($M = 3.70$, $SD = 0.88$) were likewise rated as high priorities.

AR media for visualizing abstract mathematical concepts received a moderate rating ($M = 3.10$, $SD = 0.92$), making it the lowest-rated requirement among the eight aspects examined. Overall, the findings indicate that teachers prioritized practical usability and implementation feasibility alongside instructional quality. Their expectations extend beyond the visual capabilities of AR to include accessible operation, interactive content, curriculum relevance, offline access, teacher preparation, and institutional support. Thus, prospective AR-based mathematics media should be designed not only to provide advanced visualization but also to function effectively within the practical conditions of elementary-school classrooms.

4.6. Digital Use, AR Experience and Perceptions

To extend the descriptive needs assessment, three exploratory inferential analyses were conducted to examine associations among teachers' digital technology use, prior AR experience, and AR-related perceptions. Two analyses corresponded directly to RQ6 and RQ7, while the comparison of perception scores across levels of digital technology use was treated as a supplementary exploratory analysis. Holm adjustment was applied across the three tests to control the family-wise error rate, and effect sizes with 95% confidence intervals were reported to characterize the magnitude and precision of the observed patterns.

Table 10 shows that the association between digital technology use and prior AR experience yielded an unadjusted p-value of 0.031, with a moderate effect size (Cramér's $V = 0.39$, 95% CI [0.08, 0.58]). However, the association did not remain statistically significant after Holm adjustment (adjusted $p = 0.093$). Thus, although the observed pattern suggests that digital-technology use and prior AR experience may be related within the sample, the evidence was insufficient to support a statistically reliable association after correction for multiple testing.

Table 10. Exploratory Associations among Digital Technology Use, Prior AR Experience, and AR Perceptions.

Analysis	Group Structure	Test Statistic	Unadjusted p	Holm-adjusted p	Effect Size	95% CI
Digital technology use × prior AR experience	4 × 2	Fisher–Freeman–Halton exact test	0.031	0.093	Cramér's $V = 0.39$	[0.08, 0.58]
Prior AR experience and perception score	Yes (n = 19) vs. No (n = 31)	$U = 178.50$	0.041	0.082	$r = 0.29$	[0.01, 0.52]

Analysis	Group Structure	Test Statistic	Unadjusted p	Holm-adjusted p	Effect Size	95% CI
Digital technology use and perception score	Four digital-use groups	H = 8.76	0.033	0.099	$\epsilon^2 = 0.15$	[0.02, 0.28]

A similar pattern was observed for AR experience and AR perception scores. The Mann–Whitney U test produced an unadjusted p-value of 0.041 ($U = 178.50$), with a small-to-moderate effect size ($r = 0.29$, 95% CI [0.01, 0.52]). After Holm adjustment, however, the result was no longer statistically significant (adjusted $p = 0.082$). This indicates that any difference in perception scores between teachers with and without previous AR experience should be treated as exploratory rather than as a confirmed group difference.

The comparison of AR perception scores across levels of digital-technology use also produced an unadjusted significant result ($H = 8.76$, $p = 0.033$), with a moderate effect size ($\epsilon^2 = 0.15$, 95% CI [0.02, 0.28]). Nevertheless, the result did not remain significant after Holm adjustment (adjusted $p = 0.099$). Therefore, the observed variation in perception scores across digital-technology-use groups cannot be regarded as statistically conclusive in this sample.

5. DISCUSSION

The findings provide a coherent but qualified account of prospective Augmented Reality (AR) integration in elementary mathematics. Teachers expressed highly favorable views of contextualized mathematics learning, technology-supported instruction, and AR's educational potential, yet these perceptions coexisted with limited direct AR experience and substantial implementation barriers. This distinction is important because positive appraisal does not establish implementation readiness, adoption, or effectiveness. Technology-acceptance research similarly shows that perceived usefulness and ease of use are associated more directly with intention than with sustained classroom practice [16], [51]. AR-specific research further indicates that facilitating conditions, including resources, knowledge, and institutional support, shape teachers' intentions and capabilities [33]. Thus, the high perception scores observed here are best interpreted as evidence of perceived relevance and prospective acceptance rather than demonstrated readiness.

This caution is reinforced by the clustering of responses near the upper end of the perception scales. High means accompanied by ceiling effects indicate broad endorsement but reduce variability and may weaken the capacity to differentiate teachers or detect associations. This may partly explain why exploratory comparisons yielded suggestive effect sizes without surviving correction for multiple testing. Nevertheless, the pattern remains substantively informative: teachers appeared to

value AR primarily as a means of making mathematics concrete, contextual, interactive, and accessible, rather than as technological novelty. Such judgments are consistent with evidence that teachers evaluate technology partly through its compatibility with pedagogical goals, existing practices, and contextual conditions [51]. Favorable self-reports should therefore not be equated with behavioral commitment, especially when respondents have had limited opportunity to test AR under routine classroom conditions.

A central finding is the gap between general digital-technology use and AR-specific experience. While 88% of respondents reported at least moderate use of digital technology in mathematics instruction and 60% reported high or very high use, 62% had never used AR and only 8% used it often or very often. General digital familiarity therefore appears to provide a foundation rather than a substitute for AR-specific competence. This interpretation aligns with TPACK, which conceptualizes meaningful technology integration as coordination among technological, pedagogical, and disciplinary knowledge [17] and with the TARC framework, which differentiates teachers' capacities to create, use, evaluate, and manage AR resources [20]. Recent international evidence likewise shows that teachers may hold positive attitudes toward AR while reporting lower confidence in creating and managing AR experiences, with competence varying according to general digital skills and previous classroom AR use [20]. Indonesian evidence similarly indicates that digital competence predicts AR-related skills, but that readiness is not simply interchangeable with competence [23]. Readiness is therefore better understood as a configuration of appraisal, digital familiarity, direct experience, pedagogical competence, access, and institutional support.

The topic priority findings sharpen this interpretation. Three-dimensional geometry received the highest perceived need for AR visualization, followed by two-dimensional geometry and fractions, whereas numbers and measurement were rated lower. This differentiated pattern supports a content-affordance perspective: AR has its clearest rationale when learners must inspect spatial relations, vary viewpoints, manipulate objects, or coordinate two- and three-dimensional representations. Recent synthesis is consistent with this emphasis. A meta-analysis of K–12 mathematics studies reported an overall positive effect of AR on mathematics achievement, while also showing that outcomes varied according to characteristics of AR implementation [75]. A recent scoping review further identified geometry, measurement, and spatial visualization as recurrent domains in which AR may support spatial-skill development. However, effects

remain sensitive to task design, context, and assessment [7]. Broader STEM meta-analytic evidence also reports positive average effects on achievement, thinking skills, and motivation. However, such pooled estimates should not be interpreted as evidence that AR is uniformly superior across contents or settings [76]. The present ratings therefore identify plausible development priorities rather than an effectiveness hierarchy. Value-added studies should compare AR with manipulatives, diagrams, animations, or dynamic geometry software to determine when augmentation contributes unique instructional benefit.

The barrier profile indicates that adoption is embedded in a wider implementation system. Limited devices and school infrastructure were the most prominent constraints, followed by limited AR competence, insufficient training, and unequal student access to digital devices. This pattern remains consistent with established distinctions between external barriers, such as access and support, and internal or practice-related barriers involving knowledge, confidence, and pedagogical routines [55], [57]. Importantly, these constraints are complementary rather than substitutable. Teacher interest cannot compensate for insufficient student access, while providing devices does not ensure mathematically coherent integration. The contrast between generally adequate reported internet availability and continued concern about connectivity further illustrates why infrastructure should be assessed at the level of the instructional event. Wi-Fi availability alone does not guarantee adequate bandwidth, device compatibility, charging capacity, technical support, or simultaneous student access. Because institutional access to Wi-Fi, projectors, and laptops exceeded access to student smartphones and tablets in this sample, future feasibility work should measure usable learner-level access and technical reliability rather than the mere presence of school connectivity.

Professional development should be treated as part of the same implementation ecology. Teachers rated AR competence and training as substantial barriers, although these responses represent perceived constraints rather than performance-based measures of competence. Effective professional learning should therefore extend beyond procedural demonstrations of an application. Teachers need opportunities to evaluate mathematical accuracy, identify tasks in which augmentation adds representational value, connect manipulation to explanation and assessment, and rehearse classroom orchestration using realistic device configurations. This recommendation is supported by AR competence research emphasizing instructional design and resource management [20], [53] and by broader evidence that technology integration depends on the interaction of knowledge, pedagogy, resources, and context rather than isolated technical skill [54]. Training organized around lesson design, enactment, feedback, and revision is

therefore more likely to develop usable technological pedagogical mathematical judgment than decontextualized software instruction.

Teachers' desired media characteristics reinforce the same needs-driven interpretation. Interactive and engaging content received the highest requirement rating, followed by ease of use, offline functionality, institutional support, curriculum alignment, age appropriateness, and teacher training. Notably, visualization of abstract concepts was not the sole or highest concern; teachers emphasized usability, accessibility, curricular fit, and sustainability. This is important because AR can either support or burden learning depending on how information, interaction, guidance, and spatial representations are designed. Recent systematic reviews show that AR-related cognitive demands vary substantially across implementations and that meaningful design requires attention to spatiality, interaction, content complexity, guidance, and display selection [42]. The learning value of immersive technologies has likewise been shown to depend on their cognitive demands and instructional configuration [77]. A 2026 meta-analysis found a small-to-moderate average reduction in cognitive load for AR, but with very high between-study heterogeneity and significant moderation by intervention frequency and feedback form [78]. These findings argue against treating interactivity as visual stimulation alone. Interactivity should direct learners toward mathematical relationships while minimizing interface demands that compete with conceptual processing.

Offline operation and straightforward interfaces may be relevant where connectivity or classroom time is constrained. Prototype evaluation should therefore examine mathematical accuracy, technical reliability, accessibility, cognitive demand, and classroom manageability under intended device, grouping, and time conditions. Teacher participation in iterative design can help identify constraints that are difficult to anticipate outside classrooms [32]. These are development priorities suggested by the survey, not demonstrated effects of a particular design.

None of the three exploratory comparisons remained significant according to the reported Holm-adjusted values. The small purposive sample, unequal AR-experience groups, multiple comparisons, and upper-end clustering of perception scores limit inference. Larger studies could prespecify hypotheses and distinguish self-reported experience from observed competence and actual adoption. A reasonable next sequence is teacher-informed prototype development, usability and feasibility assessment, and then classroom evaluation of learning outcomes.

6. IMPLICATION

The findings indicate that AR development for elementary mathematics should be guided by specific instructional

needs rather than technological novelty. Three-dimensional geometry represents a plausible initial focus because its spatial demands align closely with AR affordances [7], [12]. This content priority is also consistent with evidence from Indonesian elementary mathematics showing persistent difficulties in mathematical representation, measurement and calculation, communication, and generalization during geometry learning [79]. Design priorities should therefore emphasize representational value, curriculum alignment, purposeful interactivity, ease of use, age-appropriate interaction, and offline or low-bandwidth functionality. Contextual and meaningful learning experiences can also strengthen students' understanding of geometric representations, particularly when abstract concepts such as cube nets are connected to familiar activities and concrete learning contexts [80].

Implementation feasibility depends on more than media design. Device availability, school infrastructure, student access, connectivity, and institutional support remain central constraints. The observed gap between general digital-technology use and direct AR experience also suggests that teacher preparation should extend beyond technical operation to include content selection, evaluation of mathematical representations, task design, classroom management, and assessment, consistent with TPACK and AR-specific competence frameworks [17], [53].

This emphasis also resonates with the broader argument that technical efficacy alone is insufficient for meaningful technology-mediated practice; human factors such as confidence, perceived capability, and context-sensitive judgment remain important considerations. In the present context, strengthening teachers' self-efficacy in selecting, adapting, and managing AR-supported mathematics activities may therefore be as important as developing their technical skills [81].

Institutional support should therefore accompany AR development through adequate resources, technical assistance, preparation time, and opportunities for teacher experimentation. Because none of the exploratory associations remained statistically significant after Holm adjustment, digital experience and prior AR use should not be treated as established predictors of implementation. Subsequent research should evaluate prototype usability, classroom feasibility, teacher competence, and learning outcomes using larger and more diverse samples.

7. CONCLUSION

The 50 participating elementary-school teachers reported favorable perceptions of AR's prospective use in mathematics, yet 62% had no previous AR experience. Three-dimensional geometry had the highest perceived need for AR visualization among five topics. Limited devices and infrastructure, perceived competence and training needs, and student access were prominent

barriers. Teachers rated interactive content, usability, offline operation, curriculum alignment, age-appropriate design, institutional support, and training as relevant requirements.

The reported exploratory comparisons did not remain statistically significant after Holm adjustment. With cross-sectional self-report data from a small purposive sample, the study supports a teacher-informed needs assessment, not claims of AR effectiveness, causal relationships, or demonstrated readiness. The findings can guide prototype development and subsequent usability, feasibility, and classroom evaluations in elementary mathematics.

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CONFLICTS OF INTEREST

The authors declare that they have no competing interests or conflicts of interest related to this study.

DATA AVAILABILITY

The datasets utilized and analyzed during this research are available from the corresponding author upon reasonable request.

ETHICAL STATEMENTS

The authors confirm that the study complied with all applicable local laws, ethical standards, and institutional guidelines, including obtaining approval from relevant ethics committees.

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