



Connecting Spatial Reasoning and the 4Cs in Primary Geometry Through an Integrative Review and Instructional Framework

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Abstract

Spatial reasoning is important for primary geometry learning, yet research linking spatial processes with critical thinking, creativity, communication, and collaboration (the 4Cs) remains fragmented across instructional traditions. This review aims to synthesize how spatial reasoning and 4C-related classroom actions can be aligned in primary geometry and to develop an instructional framework. The review employed an integrative approach to 32 peer-reviewed publications published between 2021 and 2026, combining qualitative appraisal, thematic comparison, and conceptual synthesis. The findings identified five instructional clusters: dynamic digital visualization; construction and manipulatives; inquiry and problem solving; embodied and language-rich activities; and collaborative or project-oriented learning. Across these clusters, spatial transformation, representation, prediction, explanation, and perspective coordination provided opportunities for observable 4C-related actions. However, studies rarely assessed spatial reasoning alongside all four competencies, limiting conclusions about the effectiveness of integrated instruction. The resulting 4C–Spatial Geometry Framework (4C-SGF) links spatial objectives, representational resources, observable classroom actions, and formative assessment evidence. This review contributes an evidence-informed framework for designing and investigating integrated primary geometry lessons, with implications for task development and future empirical validation of the proposed indicators and learning outcomes.

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1. Introduction

Spatial reasoning deserves explicit attention in primary mathematics because learners must do more than name and recognize geometric figures: they must anticipate transformations, interpret positions, coordinate viewpoints, and explain relationships among representations. These operations connect children's experiences with objects and diagrams to the more abstract geometric reasoning expected later in schooling. However, spatial activity can remain implicit when lessons prioritize naming shapes or reproducing familiar examples rather than articulating what changes, what remains invariant, and why a



representation is valid. Gilligan-Lee et al. (2022) argue for a more visible place for spatial thinking in mathematics curricula, while Schenck and Nathan (2024) document continuing conceptual and measurement difficulties across the field. The educational problem is therefore not simply a shortage of engaging geometry activities, but an insufficiently specified connection between the spatial operation a task demands and the evidence of reasoning that teachers can observe.

The consequences of this problem are especially salient in elementary geometry, where children encounter symmetry, orientation, transformations, area, three-dimensional structures, and increasingly complex representations. A learner may correctly identify a cube while struggling to predict the arrangement of its faces after unfolding, or may recognize a mirror image without being able to justify the correspondence between its parts. Reviews report persistent challenges with geometric conceptualization and the transition from concrete to formal representations (Juman et al., 2022; Trimurtini et al., 2022; Crompton & Ferguson, 2024). Hasanah et al. (2024) similarly describe variation in primary pupils' spatial-reasoning performance. Such evidence should not be read as demonstrating one universal developmental sequence or a single cause of difficulty. Rather, it establishes a curricular need to distinguish visualization, rotation, orientation, composition–decomposition, and spatial explanation so that activities and formative assessment are matched to the intended mathematical learning.

A separate educational discourse emphasizes the four competencies commonly identified as the 4Cs: critical thinking, creativity, communication, and collaboration. Elementary project-based and interdisciplinary studies describe classroom arrangements that provide opportunities for these forms of participation (Rati et al., 2023; Ye & Xu, 2023; Amroni et al., 2024; Dafit et al., 2024). However, broad 4C labels do not explain what counts as critical reasoning, a creative solution, or productive collaboration in a particular geometry task. For example, asking children to work together on a worksheet is not equivalent to asking them to reconcile conflicting spatial viewpoints. Likewise, generating an attractive design is not necessarily evidence of geometric creativity unless the design satisfies a mathematical constraint. Thus, the key integration problem concerns how disciplinary spatial demands become observable 4C-related actions, rather than whether geometry and the 4Cs are individually desirable educational goals.

This integration can be conceptualized by combining a social account of learning with research on representations and embodied mathematical reasoning. Vygotsky's (1978) perspective foregrounds language, shared artifacts, and interaction in the development of understanding, while Nathan et al. (2021) and Thom et al. (2024) show why gesture and changing representations are meaningful objects of analysis in geometric activity. These perspectives suggest

that externalizing a predicted rotation, testing a model, questioning a peer's explanation, and revising a shared construction may connect cognitive work with social participation. They do not demonstrate that all four competencies improve automatically whenever learners manipulate objects or discuss geometry. The proposed connection must remain tied to the task: what spatial relation is examined, which explanation or alternative must be produced, how peers' differing representations become consequential, and what evidence distinguishes correct reasoning from mere participation.

Evidence about spatial interventions further underscores the importance of specific tasks and outcomes. In a meta-analysis of 29 controlled studies involving 3,765 participants, Hawes et al. (2022) reported average improvements in mathematics performance following spatial training (Hedges' $g = 0.28$) and larger gains in trained spatial thinking ($g = 0.49$). Crucially, transfer varied according to intervention characteristics and the proximity of assessed mathematical outcomes to the training experience. Lowrie and Logan (2023) likewise examine mechanisms of transfer rather than treating it as an automatic consequence of visualization practice. Adams et al. (2023) extend this question to secondary geometry and measurement, illustrating why conclusions should attend to the alignment between instructional demands and outcomes. For primary geometry, these findings caution against using general mathematics achievement or broad 4C ratings as interchangeable proxies for the specific spatial reasoning practiced in an activity.

Research offers multiple ways to create such task alignment. Dynamic visualizations, including augmented reality and interactive geometry software, can expose transformations and changing perspectives (Hanid et al., 2022; Özçakır & Çakıroğlu, 2022; Ikhsan et al., 2024). Physical construction, LEGO, origami, and design challenges make relations among parts and wholes available for manipulation and revision (McDougal et al., 2024; Zhu et al., 2024; Habeeb, 2025; Ridgley et al., 2025). Inquiry-centered and gesture-rich activities emphasize conjecture, demonstration, explanation, and coordinated representations (Korkmaz & Yılmaz, 2022; Nathan et al., 2021). These approaches differ in the operations they privilege, the ages and settings in which they were studied, and the outcomes they assessed. Consequently, they should be synthesized in terms of their instructional affordances and documented evidence, not ranked as if they had been tested in a common comparative experiment.

A precise gap emerges at the intersection of these literatures. Reviews of spatial learning provide cognitive classifications, intervention typologies, and cautions about transfer (Woolcott et al., 2022; Schenck & Nathan, 2024; Suparman et al., 2024; Yaacob & Mahmud, 2026), whereas research on the 4Cs frequently treats them as broad instructional or developmental outcomes (Rati et

al., 2023; Amroni et al., 2024). Within the publications examined here, relatively few investigations assess a named geometry-specific spatial operation together with all four competencies using directly comparable measures. It therefore remains unclear how teachers should distinguish authentic integration from the mere presence of group work, presentations, digital tools, or open-ended activities. The gap is one of instructional specification and evidence alignment: the available studies provide relevant components, but not a sufficiently explicit account of how spatial targets, 4C-related actions, and observable indicators fit together in primary geometry.

Accordingly, this integrative review seeks to answer three connected questions: which instructional approaches recur in research relevant to primary spatial geometry; what geometry-specific actions can reasonably be associated with critical thinking, creativity, communication, and collaboration; and how can these relationships be organized into an assessable instructional design framework? The review synthesizes 32 reported publications from 2021 to 2026 and develops the proposed 4C–Spatial Geometry Framework (4C-SGF). The framework aligns a target spatial operation, a suitable representation or tool, deliberately elicited 4C-related actions, and observable evidence of geometric and participatory performance. Its originality lies in making this alignment explicit, not in claiming a newly demonstrated causal pathway or validated intervention. Given the heterogeneity and incompletely recoverable selection records of the existing corpus, the conclusions are formulated as evidence-informed design propositions requiring subsequent classroom and measurement testing.

2. Methods

This study employed a structured integrative literature review with framework synthesis. This approach was appropriate because the research questions require a conceptual connection between two partly separate bodies of scholarship: spatial reasoning and geometry education, and pedagogy organized around critical thinking, creativity, communication, and collaboration (4C). The evidence base encompasses different learner populations, instructional settings, research designs, and outcome measures. Accordingly, the review sought to identify recurring instructional mechanisms, distinguish direct evidence from conceptual correspondences, and derive an instructional framework; it did not aim to pool effect sizes or provide an exhaustive bibliometric account.

Literature identification was conducted and updated in August 2026. The search prioritized records indexed in ERIC and the Directory of Open Access Journals (DOAJ), supplemented by broader scholarly web searches and backward reference checking. Publication details were checked against publisher and journal platforms, including Springer Nature, Frontiers, Wiley, and SAGE; these checks supported source verification rather than constituting a separate

intervention dataset. Search combinations addressed three related concepts: spatial abilities (e.g., “spatial reasoning,” “spatial thinking,” “mental rotation,” and “spatial visualization”); school mathematics and geometry (e.g., “primary school,” “elementary mathematics,” and “geometry education”); and 4C-oriented learning (e.g., “4C skills,” “critical thinking,” “creativity,” “communication,” and “collaboration”). Examples of the reported combinations included “spatial reasoning” AND “primary school” AND geometry, “spatial visualization” AND primary mathematics, and “4C” AND (mathematics OR geometry). The search focused mainly on peer-reviewed publications from 2021 to 2026 to reflect recent pedagogical and technological developments.

Publications were considered eligible when they (a) were peer-reviewed journal articles or rigorous scholarly reviews; (b) examined spatial reasoning, geometry learning, one or more 4C competencies, or instructional approaches with an identifiable connection to these constructs; (c) concerned primary or elementary learners, early-childhood or closely related school contexts, or broader reviews with clear implications for primary mathematics; and (d) provided enough methodological or conceptual detail to support interpretation. Records were excluded if they duplicated another source, addressed advanced technical geometry without educational relevance, lacked an identifiable educational context, or offered unsupported commentary. These criteria yielded a core evidence base of 32 contemporary peer-reviewed publications. Vygotsky (1978) was retained separately as a foundational theoretical source, not counted among the 32 contemporary publications or treated as current empirical evidence. Evidence from non-primary settings was interpreted for its potential relevance to primary geometry rather than treated as direct evidence about primary pupils.

The included publications were appraised qualitatively for publication legitimacy, transparency of the study or review design, clarity of participants or review scope, alignment between the studied constructs and the review questions, and directness of the reported evidence. Because the corpus includes intervention, qualitative, mixed-methods, review, and conceptual studies, a single numerical quality score was not imposed across research designs. Instead, the interpretation differentiated studies that directly examined spatial learning outcomes from studies addressing 4C-related participation or broader pedagogical mechanisms. Direct empirical evidence was given greater weight when characterizing spatial-learning outcomes; indirect and conceptual evidence was used to explain possible instructional connections without implying that unmeasured spatial or 4C gains had been demonstrated.

Information from the included publications was organized into five extraction categories: educational level and participants; spatial construct or 4C competency; instructional approach; learning tools or representations; and reported findings or educational implications. Spatial constructs were coded as

visualization, mental rotation or transformation, orientation or perspective taking, composition–decomposition, spatial language or representation, and broader spatial reasoning. Instructional approaches were grouped as dynamic digital visualization, physical manipulatives or construction, inquiry or problem solving, embodied learning, collaborative discourse, project-based learning, and combinations of these approaches. For the 4C mapping, a distinction was made between competencies explicitly examined by the cited study and correspondences inferred from identifiable classroom actions. For example, evaluating alternative geometric solutions was mapped to critical thinking, whereas producing multiple valid constructions was mapped to creativity. An inferred correspondence was treated as an analytical interpretation, not as evidence that the particular 4C competency had been experimentally improved.

Synthesis proceeded through three connected analytical stages. Descriptive mapping first identified the instructional approaches, spatial targets, and outcomes reported in the included sources. Thematic comparison then examined recurring task features, including manipulation of representations, physical construction, prediction and justification, spatial explanation, perspective comparison, iterative design, and peer interaction. Finally, framework synthesis mapped these features to the 4Cs and specified possible task designs and observable indicators for the proposed 4C–Spatial Geometry Framework (4C-SGF). Proposed links were judged against the cited literature and an established conceptual rationale; nevertheless, these links are interpretive rather than independently tested relationships. The review did not produce pooled estimates, formally score risk of bias, or implement a prospectively registered systematic review protocol. Therefore, database-specific retrieval counts, full search strings, and records of exclusions were not available in the source documentation and cannot be retrospectively reconstructed. These constraints limit reproducibility and the extent to which the corpus can be described as exhaustive. Only published scholarly sources were examined, with no recruitment of participants or collection of personal information.

3. Results

3.1 Instructional Approaches Identified in Spatial-Learning Research

The 32 peer-reviewed publications included in the synthesis encompassed studies of spatial learning, reviews of spatial-reasoning interventions, and investigations of 4C-oriented pedagogy in primary or related educational settings. Their different learner groups, research designs, and outcome measures did not support a common effect estimate or a ranking of instructional approaches. Instead, five recurring instructional clusters were identified: dynamic digital visualization; physical construction and manipulatives; inquiry and problem solving; embodied and spatial-language activities; and collaborative, project- or

creation-oriented learning. Studies reporting spatial outcomes and studies reporting broader 4C outcomes were considered complementary but distinct strands of evidence.

Dynamic digital visualization was a recurrent cluster. The reviewed work discussed GeoGebra, augmented reality, interactive three-dimensional environments, and other tools through which geometric objects could be rotated, transformed, inspected, or compared. Hanid et al. (2022) reported positive outcomes for augmented-reality geometry activities integrated with computational-thinking processes, while Özçakır and Çakıroğlu (2022) examined spatial strategies supported by augmented reality. GeoGebra-related studies addressed manipulable representations of geometric relationships (Alves et al., 2022; Ikhsan et al., 2024). Reviews also identified technology-supported approaches among interventions targeting spatial visualization and mental rotation (Suparman et al., 2024; Yang et al., 2026; Yaacob & Mahmud, 2026). Across these sources, recurring task features included learner-controlled manipulation, comparison of viewpoints, and inspection of transformations; the studies did not use a single common measure of these processes.

Physical construction and manipulatives formed a second cluster. Such activities involved coordinating visual predictions with changes to tangible objects. McDougal et al. (2024) linked LEGO-based construction training with spatial and mathematics learning, while Bower et al. (2025) reported associations between early concrete and digital spatial experiences and subsequent spatial and mathematics outcomes. Origami and folding tasks also required learners to follow sequences of transformations and use spatial language (Ridgley et al., 2025). The spatial actions represented in this cluster included building, folding, composing, decomposing, and checking imagined configurations against physical results.

Inquiry and problem solving constituted a third cluster. Korkmaz and Yılmaz (2022) reported gains in children's geometric and spatial thinking in an inquiry-based mathematics context. Harris et al. (2021) examined how coordinating static and interactive representations can make mathematical relationships accessible during problem solving. Across these sources, students were asked to predict, compare, test, select, or justify representations rather than only reproduce a demonstrated solution. These actions provide observable points of connection with critical thinking, although a spatial-learning outcome does not by itself establish improvement in the full 4C competency.

Embodied activity and spatial language formed a fourth cluster. Nathan et al. (2021) documented the participation of gesture in geometric reasoning, and Thom et al. (2024) described spatial experiences involving bodily movement, orientation, and object transformation. Ridgley et al. (2025) reported increased spatial language alongside reduced mathematics anxiety in origami-related

activities. These studies drew attention to gesture, movement, verbal descriptions, and relational terms such as above, behind, rotated, and viewpoint as ways to express spatial relationships. However, the studies did not uniformly assess all of the same geometry outcomes or communication competencies.

Collaborative, project-based, and creation-oriented learning constituted the fifth cluster and provided principally 4C-focused evidence. Rati et al. (2023) reported improvements in elementary students' 4C competencies through higher-order-thinking-oriented e-project-based learning, while Amroni et al. (2024) reported positive 4C outcomes in project-based learning. Dafit et al. (2024) documented variation in elementary learners' demonstrated 4C abilities, and Ye and Xu (2023) discussed interdisciplinary thematic learning as a context for developing these competencies. The recurring classroom activities were shared production, explanation, comparison of ideas, and collaborative revision. Because these sources did not necessarily assess spatial visualization, mental rotation, or orientation, their contribution to the present synthesis is evidence about 4C-related learning processes rather than direct evidence of gains in spatial ability.

3.2 Spatial Actions Associated with the Four Competencies

Cross-study mapping identified four correspondences between spatial tasks and the 4C model. Critical thinking was associated with comparing viewpoints, verifying transformations, detecting incompatible configurations, and justifying geometric decisions (Harris et al., 2021; Korkmaz & Yilmaz, 2022). Creativity was associated with generating multiple valid constructions, rearranging components, and designing or transforming geometric patterns (Zhu et al., 2024; Scippo et al., 2025). Communication was represented through spatial vocabulary, gesture, diagramming, and translation between verbal and visual descriptions (Nathan et al., 2021; Ridgley et al., 2025). Collaboration corresponded to coordinating perspectives, negotiating alternatives, and revising shared products, drawing on the broader elementary 4C literature (Rati et al., 2023; Amroni et al., 2024). These connections represent the review's analytical mapping of evidence strands, not a finding that all four competencies and spatial outcomes were jointly tested in one instructional intervention. Table 1 displays these instructional clusters, the spatial actions associated with them, and the proposed 4C links. The cited studies provide representative support for the relevant evidence strands; a 4C correspondence should not be interpreted as an outcome directly measured by every cited spatial-learning study.

Table 1.
Instructional approaches, spatial affordances, and 4C processes.

Approach	Spatial affordance	Proposed 4C link and cited literature
Dynamic digital visualization	Rotation, transformation, perspective, and invariant relationships	Critical thinking, communication, and creativity; Hanid et al. (2022), Ikhsan et al. (2024), Yang et al. (2026)
Construction and manipulatives	Composition-decomposition, 3D visualization, and part-whole coordination	Creativity, collaboration, and communication; McDougal et al. (2024), Bower et al. (2025), Ridgley et al. (2025)
Inquiry and problem solving	Prediction, comparison, verification, and strategy selection	Critical thinking and communication; Harris et al. (2021), Korkmaz & Yılmaz (2022)
Embodied and language-rich activity	Orientation, gesture-supported transformation, and spatial vocabulary	Communication and critical thinking; Nathan et al. (2021), Thom et al. (2024)
Project and collaborative learning	Perspective negotiation, shared modeling, and iterative revision	4C competencies as broad learning outcomes; Rati et al. (2023), Amroni et al. (2024), Ye & Xu (2023)

Source: Author’s synthesis of the reviewed literature. Spatial affordances and 4C correspondences are analytically mapped; the cited studies did not uniformly measure both spatial outcomes and 4C competencies.

The mapping further distinguished the principal spatial targets addressed by these activities. Visualization was linked to drawing, construction, dynamic geometry, and decomposition; mental rotation or transformation to physical or digital rotation, folding, and comparison of changed figures; and orientation or perspective taking to movement, viewpoints, and three-dimensional reconstruction. Composition–decomposition was associated with blocks, tangrams, tessellations, origami, and nets, while spatial language and representation appeared in several clusters. These are construct–task associations identified in a heterogeneous literature, not estimates of relative intervention effectiveness.

3.3 Proposed 4C–Spatial Geometry Framework and Learning Indicators

These mapped relationships were consolidated into the proposed 4C–Spatial Geometry Framework (4C-SGF). The framework specifies four kinds of observable action in geometry tasks: critical thinking through verifying, comparing, and justifying spatial relationships; creativity through generating, redesigning, and transforming valid representations; communication through describing, diagramming, gesturing, and translating spatial information; and collaboration through coordinating perspectives, negotiating evidence, and jointly revising constructions. Table 2 organizes each competency alongside its spatial process and an illustrative task or indicator. The resulting structure is a

conceptual product of the synthesis rather than an empirically validated classroom intervention or assessment instrument.

Table 2.

Operational structure of the 4C–Spatial Geometry Framework (4C-SGF).

4C competency	Spatial process	Illustrative task and indicator
Critical thinking	Evaluate and justify spatial relations.	Choose valid cube nets, detect impossible configurations, and justify decisions with spatial evidence.
Creativity	Generate and transform representations.	Create several valid nets, decompositions, patterns, or structures under the same constraints.
Communication	Externalize and translate spatial representations	Describe a hidden structure using precise spatial language, diagrams, or gesture so a partner can reconstruct it.
Collaboration	Coordinate perspectives and jointly revise models	Combine distributed viewpoints, negotiate conflicting evidence, and modify a shared 3D construction.

Source: Author's proposed 4C-SGF; indicators have not been empirically validated.

A four-step lesson-design sequence was derived: identify the spatial target; select a manipulable representation or tool; specify the required 4C actions; and assess spatial accuracy alongside the quality of reasoning or interaction. Table 3 illustrates applications to primary geometry topics. The examples are proposed designs, not lessons evaluated as a unified 4C-SGF intervention.

Table 3.

Examples of 4C-SGF lesson design in primary geometry.

Geometry focus	4C-integrated spatial task	Potential learning indicators
2D composition	Teams create several target figures from identical tangram pieces and explain different solutions.	Correct composition, solution variety, and explanation of part-whole relations.
3D solids and nets	Pairs predict, test, and redesign cube nets.	Prediction accuracy, justification, and alternative valid nets.
Views of objects	Groups reconstruct a block model from distributed front, side, and top views.	Perspective coordination, spatial language, and model accuracy.
Symmetry and transformation	Learners identify errors in reflected or rotated figures and create a new symmetric design.	Error detection, transformation reasoning, and creative design.
Coordinate movement	Pairs give route instructions under constraints and compare efficient routes.	Directional accuracy, communication precision, and strategy evaluation.

Source: Author's illustrative 4C-SGF tasks; not empirically tested.

4. Discussion

4.1 Spatial Tasks Connect Cognitive Operations with the Four Competencies

The central interpretive finding is that spatial thinking and the 4Cs intersect most plausibly through the design of specific geometric tasks, not through the generic adoption of active-learning terminology. The reviewed spatial studies frequently identify the representation or transformation being practiced, while the 4C studies often emphasize participation, student products, or more general competency outcomes (Gilligan-Lee et al., 2022; Rati et al., 2023; Amroni et al., 2024). This asymmetry explains why apparently compatible instructional approaches cannot establish an integrated effect on their own. A learner may collaborate without engaging in demanding spatial reasoning, or reason spatially without being asked to communicate an explanation. Through social constructivism and embodied accounts of mathematics, the potential intersection becomes conceptually clearer: representations are generated and manipulated individually but can be articulated, challenged, and modified in interaction (Vygotsky, 1978; Nathan et al., 2021; Thom et al., 2024). This is a theoretically plausible interpretation of the synthesis, not an experimentally established mechanism.

Critical-spatial reasoning is most convincingly operationalized when learners evaluate a geometrically consequential claim. Inquiry and spatial problem-solving studies emphasize prediction, comparison, testing, and justification (Harris et al., 2021; Korkmaz & Yılmaz, 2022). These activities become critical thinking only when a judgment is supported by the spatial properties that make an answer correct or incorrect: for instance, explaining why a particular arrangement of square faces can fold into a cube or why one image is not a valid rotation of another. This distinction matters because an explanation rubric that rewards confidence or verbal fluency might misclassify participation as mathematical reasoning. Hawes et al. (2022) also show that improvements in trained spatial skills cannot be presumed to transfer uniformly to distant mathematics outcomes. Hence, classroom evidence should distinguish accurate geometry from the quality of the argument offered to establish it.

Creative-spatial generation provides a second, complementary mechanism of integration: learners are required to construct multiple representations while maintaining explicit geometric constraints. Design and construction research offers relevant instances of open-ended spatial production (Zhu et al., 2024; Habeeb, 2025; Scippo et al., 2025), but openness alone does not guarantee evidence of geometric creativity. What distinguishes the proposed indicator is the simultaneous assessment of representational variety and mathematical admissibility. Producing several valid nets of one solid demonstrates a different

form of flexibility from decorating a single net or creating many invalid layouts. This distinction may help educators give formative feedback that preserves both exploration and rigor. It remains a proposed operational definition rather than a validated scale of creativity; studies directly comparing the indicator with established creativity and spatial assessments are required.

Communicative-spatial representation matters because internal spatial images are otherwise difficult for teachers or peers to inspect. Explaining a viewpoint shift, coordinating a gesture with a diagram, or using precise language for relative position makes reasoning available for feedback and disagreement. Embodied geometric reasoning offers a theoretical basis for treating gesture as part of mathematical meaning-making (Nathan et al., 2021; Thom et al., 2024), while language-focused spatial activities provide a complementary route to externalizing relations (Ridgley et al., 2025). However, communication quality should not be inferred merely from the number of spoken turns or the elegance of a presentation. The relevant evidence is whether a representation and its explanation preserve the spatial structure of the task. Thus, an assessment can record the accuracy of orientation terms, consistency between a verbal description and a model, and the learner's ability to identify an error in another description.

Collaboration is spatially substantive only when participants must coordinate information or resolve incompatible representations to complete the geometry problem. Elementary project-based studies make collaborative learning a credible pedagogical context (Rati et al., 2023; Amroni et al., 2024), yet their broader 4C outcomes cannot substitute for evidence of collaborative spatial reasoning. Consider a group receiving separate front, side, and top views of a structure. The task creates an information dependency: members must translate their partial views into a common model, justify revisions, and check the result against every constraint. In Vygotskian terms, dialogue and shared artifacts may mediate the refinement of understanding (Vygotsky, 1978). Nevertheless, a successful group product cannot be attributed equally to each pupil. Future studies should collect individual spatial measures alongside observations of negotiation to test the proposed learning pathway.

These four interpretations explain the design logic of the 4C–Spatial Geometry Framework (4C-SGF). Its value does not reside in introducing four additional mathematics outcomes; instead, it obliges the designer to specify a spatial target before selecting a tool, social arrangement, or assessment prompt. A mental-rotation task, for example, calls for evidence different from a composition–decomposition task, even if both involve discussion and collaborative production. This principle is consistent with meta-analytic evidence that transfer depends partly on the relationship between training and assessed outcomes (Hawes et al., 2022) and with reviews highlighting fragmented

classifications and measures of spatial ability (Schenck & Nathan, 2024). The framework can therefore improve conceptual precision in lesson planning, but no reviewed study validates the complete four-step sequence or demonstrates its superiority to an alternative geometry pedagogy.

Table 2 presents proposed task indicators, while Table 3 illustrates possible lesson applications. Their contribution is to make the instructional claims more observable: placing pupils in groups does not by itself establish collaboration, just as displaying a digital solid does not ensure mental rotation. In one illustrative task, group members each receive a different two-dimensional view of an unknown block structure and must construct a model consistent with all views. The task makes communication, comparison, negotiation, and revision necessary for solving a spatial problem. Nevertheless, this is an instructional example derived from the synthesis, not a classroom trial of the 4C-SGF; its feasibility and effects remain to be evaluated.

4.2 Task-Specific Evidence Is Needed to Guide Instruction and Assessment

The implications for instructional sequencing follow from alignment rather than from an assumed hierarchy of teaching media. Physical blocks, hand movements, diagrams, augmented reality, and dynamic geometry environments afford different ways to expose relations among objects, orientations, and transformations (McDougal et al., 2024; Bower et al., 2025; Yang et al., 2026). A teacher's choice should depend on the operation children must perform and explain, their prior knowledge, and the available resources. In a composition task, physical assembly may be especially transparent; in a perspective-change task, controlled digital rotation may make a particular relation easier to inspect. Yet the reviewed studies differ in age, task, and measurement conditions, so an evidence-based hierarchy of media cannot be inferred. The proposed instructional sequence should be treated as flexible design guidance rather than a universally effective developmental progression.

Teacher mediation is central to this progression. Gagnier et al. (2022) found that elementary teachers' beliefs and self-efficacy are relevant to spatial thinking in STEM. Teachers need a language for recognizing spatial opportunities in ordinary mathematics lessons and for asking questions that make spatial processes visible. Instead of asking only "What is the answer?", a teacher might ask "How do you know these two shapes are the same after rotation?", "Can you make another structure that satisfies the same conditions?" "Describe the change without touching the object," or "Which part of your partner's explanation changed your model?" These prompts align assessment with the 4C-SGF and encourage metacognitive awareness of spatial strategies.

Assessment is the most important practical test of whether the proposed integration is meaningful. A geometry task may simultaneously provide evidence

of a correct spatial transformation and an opportunity for explanation or peer discussion, but these are different constructs and should be recorded separately. Schenck and Nathan (2024) identify the diversity of spatial classifications and instruments as a continuing obstacle to cumulative interpretation; a single undifferentiated 4C-spatial score would reproduce that problem. The 4C-SGF instead suggests dual evidence streams: task-specific geometric correctness and separately described process indicators such as justified comparisons, valid alternatives, accurate relational language, and negotiated model revisions. Agreement between observers, developmental appropriateness, content coverage, and associations with established spatial measures have not yet been established. Accordingly, the indicators are formative design suggestions, not a validated assessment instrument or evidence of changes in achievement.

Technology provides a further illustration of the distinction between instructional affordance and demonstrated learning. Augmented reality and GeoGebra can allow students to control rotations, compare views, and inspect invariant properties (Hanid et al., 2022; Ikhsan et al., 2024; Yang et al., 2026). The synthesis identifies these affordances as potentially compatible with critical evaluation, explanation, and creative transformation, but technology-supported spatial outcomes should not be taken as direct evidence of all four 4C competencies. Within the proposed 4C-SGF, digital tools would be selected when they make a spatial operation easier to manipulate or discuss; the intended learning evidence would still need to be measured rather than inferred from tool use alone.

4.3 The Framework Extends Spatial Instruction Beyond Activity Labels

The present framework contributes at the level of pedagogical specification, a narrower and more defensible claim than asserting an entirely new theory of spatial learning. Woolcott et al. (2022) synthesize interventions to clarify the relationship between spatial reasoning and primary mathematics, while Schenck and Nathan (2024) explain why competing construct taxonomies and measures complicate interpretation. Yaacob and Mahmud (2026) organize patterns of educational intervention and spatial outcomes. These contributions establish why spatial learning deserves explicit instruction and why evidence must be interpreted by task and measure. The distinctive question addressed here is what observable 4C-related actions can be required during a particular spatial operation. By specifying these actions and separating them from mathematical accuracy, the 4C-SGF may improve the design and communication of geometry lessons; its incremental contribution is conceptual clarity, pending empirical validation.

A second conceptual contribution is the distinction between competency labels and disciplinary evidence. Existing elementary 4C studies support the importance of critical thinking, creativity, communication, and collaboration as

learning aims (Rati et al., 2023; Ye & Xu, 2023; Amroni et al., 2024), but the same terms may be operationalized differently across subjects. In primary geometry, a creative response should satisfy spatial constraints, a critical explanation should appeal to geometric properties, and a collaborative revision should resolve conflicting representations rather than merely divide labor. Such specifications make the proposed framework usable as a hypothesis-generating design tool. They do not permit a conclusion that the four competencies constitute independent spatial constructs or that their simultaneous activation increases learning. This restraint is essential when synthesizing literature that rarely employs common outcome measures.

4.4 Evidence Heterogeneity Limits Claims of Integrated Effectiveness

Several limitations qualify these conclusions. The reported corpus comprises 32 publications spanning heterogeneous ages, settings, research designs, and outcomes; it therefore does not supply a common denominator for comparing intervention effectiveness. In addition, database-specific retrieval counts, a complete screening trail, and individual appraisal judgments are not available in the manuscript, making the search difficult to reproduce and precluding an SLR designation without further documentary evidence. The synthesis also brings together studies directly measuring spatial outcomes and studies examining the 4Cs in other subjects, which makes some framework links inferential rather than directly observed. The analysis has not quantified the prevalence of each proposed mechanism among the included studies or established inter-coder agreement. These limitations restrict conclusions to an integrative interpretation and a testable instructional proposition, not a systematic estimate of efficacy or a validated 4C measurement model.

The next research step should therefore separate framework validation from intervention evaluation. Expert review and teacher cognitive interviews could first establish whether the spatial operations, 4C-related indicators, and lesson examples are sufficiently distinct, age-appropriate, and usable. Pilot observations could then investigate how often proposed behaviors occur in authentic geometry tasks and whether different observers can code them consistently. Subsequent controlled classroom comparisons should assess baseline and follow-up spatial outcomes, geometric achievement, and independently rated competency processes; following Hawes et al. (2022), transfer outcomes should be selected according to their proximity to the practiced operation. Mixed qualitative and quantitative evidence could test whether explanation, alternative generation, or viewpoint negotiation mediates any observed learning differences. Finally, a genuinely systematic evidence update would require predeclared eligibility criteria, complete search strings, screening counts, an extraction table, and design-specific appraisal records.

5. Conclusion

This integrative review of 32 publications identified five recurring instructional approaches relevant to spatial thinking in primary and closely related school geometry: dynamic digital visualization, construction and manipulatives, inquiry and problem solving, embodied and language-rich activity, and collaborative or project-oriented learning. Across these studies, manipulating, transforming, comparing, constructing, and explaining spatial representations emerged as recurring learning opportunities, although the heterogeneous evidence does not establish which approach is most effective. The synthesis also identified potential connections between spatial processes and the four 4C competencies: critical thinking through evaluating and justifying spatial relations; creativity through generating and transforming geometrically valid representations; communication through spatial language and translation between representations; and collaboration through coordinating perspectives and jointly revising models. Because spatial outcomes and all four competencies were rarely assessed together, these connections represent evidence-informed conceptual mappings rather than demonstrated combined effects.

The principal scholarly contribution is the proposed 4C–Spatial Geometry Framework (4C-SGF), which aligns spatial learning objectives, representational tools, required 4C-related actions, and observable indicators within a four-step lesson-design sequence. For primary teachers, this framework offers a way to specify the geometric purpose of activities involving explanation, alternative constructions, and peer interaction, while distinguishing mathematical accuracy from the quality of reasoning and collaboration. The contribution remains conceptual: the 4C-SGF has not been validated as an integrated classroom intervention or assessment instrument. Interpretation is also limited by variation in the reviewed populations, designs, and measures, as well as the incomplete documentation of database-specific search and screening results. Future studies should first evaluate the feasibility and validity of the proposed tasks and indicators, then investigate classroom implementation, spatial learning outcomes, and transfer across grades and educational contexts. Accordingly, the framework provides a testable basis for integrated elementary geometry instruction, not evidence that its use has already improved students' spatial thinking or 4C competencies.

Declarations

Funding: The author declares no competing interests. This review analyzed published literature and did not recruit human participants; participant consent was not applicable. The publications discussed are identified in the reference list; no new participant-level dataset was collected. Grammarly was used to refine language.

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