2.9

Embedding the Core Triad: Spatial Ability, Visualisation, and Representational Literacy

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Engineers rely on visual-spatial thinking at many stages of practice, from interpreting technical drawings to simulating system behaviour before construction begins. Simultaneously, engineering educators assign complex spatial tasks often without explicitly and deliberately teaching the underlying cognitive skills those tasks demand. This chapter addresses that gap by presenting visual-spatial thinking as a structured, trainable competency built on three interdependent elements: spatial ability (the cognitive capacity to mentally manipulate visual images), visualisation (the active process of applying that capacity to engineering problem solving), and representational literacy (the skill of creating and communicating through engineering's visual language). Together, these form the Core Triad. The chapter argues that all three elements are essential for engineering practice, demonstrably trainable through targeted instruction, and central to equitable access to the discipline. We present five evidence-based implementation strategies (low-stakes sketching, physical and digital manipulatives, anonymous peer feedback, concept mapping, and dedicated visual-spatial skills modules), along with practical guidance and supporting research evidence. The chapter concludes with a synthesis of teaching recommendations designed to foster the growth-oriented culture in which these strategies are most effective. The overall aim is to equip educators with a coherent framework for developing the Core Triad skills in all students, not only those who innately have them.

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1 Definition

Visual-spatial thinking is a core mode of thought in engineering, underpinning how problems are understood, solutions are conceived, and systems are designed (Ferguson, 1992; Kozhevnikov et al., 2007; Raju & Sorby, 2024). An engineer must look at a drawing, a simulation, or a dataset and be able to see the latent behaviour within (e.g., visualising assembly sequences before construction, simulating fluid flow through a valve design, or walking mentally through the ergonomic reality of a design a decade later). Crawley et al. (2014) conceptualise engineering practice as a lifecycle of conceiving, designing, implementing, and operating products, processes, and systems across disciplines. In light of this, visual-spatial thinking could be understood as underpinning multiple stages of engineering design and problem solving, from concept to validation.

Despite its foundational role, visual-spatial thinking often remains an implicit expectation rather than an explicit and deliberate target of instruction (Ha & Fang, 2016; Sorby, 2009). When students struggle, they are frequently viewed as lacking engineering intuition (Newcombe, 2010) rather than as learners who need deliberate training in a distinct and teachable skill set (Sorby, 2009; Uttal et al., 2013). This chapter addresses this disconnect by presenting visual-spatial thinking not as an inherent attribute, but as an active, learnable process structured around the Core Triad of three interdependent elements – namely, spatial ability, visualisation skills, and representational literacy.

Spatial ability is the cognitive foundation, defined as the capacity to generate, retain, and mentally manipulate visual images of objects in two- and three-dimensional space (Buckley et al., 2018; Lohman, 1994). It underlies core engineering tasks such as interpreting technical drawings, manipulating computer-aided design (CAD) models, and supporting the spatial reasoning that runs through engineering practice. Spatial ability is not a fixed trait, as meta-analyses confirm that targeted instruction produces significant, lasting improvements, making it a learnable competency (Uttal et al., 2013).

Visualisation skills are the active, applied processes that draw on spatial ability to construct, interpret, and work with mental images in order to understand and solve engineering problems (Raju & Sorby, 2024; Sorby et al., 2013). This competency is not the simple act of passive observation but an engaged cognitive act that enables an engineer to mentally see how a system behaves before it is built or mentally simulate physical phenomena under conditions not yet tested.

Representational literacy completes the triad by addressing how the above visual-spatial thinking is externalised, communicated, and refined. It refers to proficiency in creating, interpreting, and working flexibly with the visual language of engineering such as via technical drawings, schematics, free-body diagrams, and digital models (Johri & Lohani, 2011). These representations function as cognitive artefacts that make abstract thought tangible and open to critique, revision, and collaboration.

The three elements form a continuous and mutually reinforcing cycle. Spatial ability provides the cognitive capacity that enables visualisation, visualisation is made communicable through representational literacy, and the act of creating and working with external representations in turn strengthens spatial ability.

When a student sketches a 3D component, they simultaneously engage spatial ability (mentally rotating the object), practise visualisation (reasoning and deciding what to emphasise), and develop representational literacy (applying technical drawing and mapping conventions). In other words, a student who can mentally rotate simple geometric forms but struggles to apply this capacity to interpret a complex engineering assembly may have strong spatial ability but underdeveloped visualisation. Similarly, a student who can reason visually but cannot produce an accurate sketch or read a technical drawing may have underdeveloped representational literacy despite strong and intact visualisation. The cycle operates as a unified whole and recognising it allows educators to diagnose precisely where a student may be struggling — whether with internal spatial cognition, the functional applicability of visualisation, or with its externalisation; thus, diagnostic distinction can directly support instructional choices.

We propose the term Core Triad to capture the integrated relationship between these three elements, as existing literature has tended to treat them separately (e.g. Johri & Lohani, 2011; Sorby, 2009). The strategies in Section 3 are designed to support practical fluency across all three elements.

2 Why teach the Core Triad of spatial ability, visualisation, and representational literacy?

The case for deliberate and explicit instruction in the Core Triad rests on three pillars: these skills are essential and are highly associated with success in engineering practice, design, and education (Buckley et al., 2018; Ferguson, 1992; Wai et al., 2009); they are malleable and trainable (Newcombe, 2010; Uttal et al., 2013); and developing them is a meaningful equity strategy that is fundamental to inclusive pathways into the field of engineering (Sorby et al., 2018). Strategies and examples supporting the practical implementations of these pillars are outlined in Section 3.

2.1 Essential for engineering practice and learning

The Core Triad is not an ancillary or subsidiary skill set; it is a fundamental mechanism through which engineering thought operates. Consider a student designing a combustor mock-up. They deploy spatial ability to navigate the nested geometry of casing, liner, injector arrays, and cooling passages; visualisation to mentally simulate assembly sequences and foresee tooling conflicts; and representational literacy to translate this understanding into manufacturing drawings and exploded-view diagrams for collaborators. A failure in any one element (i.e., a misjudged clearance, an unseen assembly conflict, or an ambiguous drawing) renders the overall work unfit for purpose.

Therefore, the pedagogical implication is clear that if the Core Triad is the mechanism of expert practice, instruction must develop this integrated competency deliberately.

Moving fluidly from mental modelling to dynamic visualisation to accurate representation is a cognitive skill (or cycle) that can, and must, be explicitly taught, scaffolded, and practised (Ha & Fang, 2016; Porat & Ceobanu, 2024; Sorby et al., 2013). It cannot be assumed to arrive innately with students, nor to be absorbed passively. As engineering evolves to address interdisciplinary challenges in design and advanced manufacturing, this capacity for visual problem solving becomes more central to innovation and technical mastery (Crawley et al., 2014).

2.2 Malleable, trainable, and consequential

Spatial ability has robust predictive validity in engineering, adding substantial forecasting power over mathematical or verbal aptitude alone, and longitudinal studies confirm that spatial skills in adolescence strongly predict both entry into and long-term success in STEM fields, even after controlling for the other aptitude measures (Berkowitz & Stern, 2018; Wai et al., 2009). For educators, the key insight is that this predictive relationship exists because the spatial skills assessed are the same ones required for successful professional engineering and engineering-related practice (Hegarty, 2010; Lubinski, 2010; Wai et al., 2009).

Meta-analytic evidence demonstrates that spatial skills are malleable and respond durably to structured training (Newcombe, 2010; Sorby, 2009; Uttal et al., 2013). Therefore, they are learnable competencies, not fixed traits. Gains acquired transfer to related cognitive and STEM-relevant task success (Hawes et al., 2022; Sorby et al., 2013; Uttal et al., 2013). The educational imperative is therefore not selection of students who innately possess this skill, but development of this skill in all students.

Spatial ability can be assessed and tracked with a validated instrument such as the Purdue Spatial Visualisation Test: Rotations (PSVT:R) (Yoon, 2011), which is widely used in engineering, CAD, and STEM education (Maeda et al., 2013; Sorby, 2009). Similarly, spatial ability can be captured using the Mental Rotation Test (MRT) (Gómez-Tone et al., 2022; Vandenberg & Kuse, 1978). These tools allow educators to diagnose student needs and measure the impact of instruction.

2.3 A strategy for equity and inclusion

Disparities in spatial skills among entering students often reflect differences in prior opportunity, such as access to spatially rich early activities shaped by early education (Newcombe & Frick, 2010), gender (Liben, 2015), and socioeconomic background (Levine et al., 2005), rather than inherent aptitude. Moreover, disparities may surface due to neurological variation, such as aphantasia (Muraki et al., 2023).

Targeted spatial instruction is therefore a powerful equaliser. The greatest gains from training are often seen among students who start with lower scores (Sorby, 2009; Uttal et al., 2013), and structured interventions have improved retention among underrepresented groups in engineering (Sorby & Baartmans, 2000; Sorby et al., 2018). Explicit development of the Core Triad is therefore a proactive strategy for widening access and ensuring that pathways into engineering are opened, not narrowed, by the training we provide (Hsi et al., 1997; Sorby et al., 2018; Stieff & Uttal, 2015).

3 Forms of implementation

Instruction in the Core Triad is most effective when it also accounts for the affective context in which students encounter visual-spatial tasks. Many engineering students experience perfectionism (Al Kakoun, 2023; Al Kakoun et al., 2024), anxiety (Brotherton et al., 2025), or a fixed-mindset belief about their ability (Stump et al., 2014; Yeager & Dweck, 2012). This may lead them to mistakenly believe that visual-spatial ability is an innate gift rather than a trainable competency, causing fear-based frustration or avoidance when confronted with tasks such as mental rotation or diagram interpretation. Stereotype-based attributions for the gender gap in spatial tasks have similar performance-hindering effects (Moè, 2012). These projections are not signs of low ability, but barriers to engagement that structured teaching can directly counter. Further, cognitive science indicates that aphantasia (reduced or absent voluntary mental imagery) affects roughly 4% of the population (Dance et al., 2022), with implications for how mental imagery and embodied simulation are exercised during conceptual processing (Muraki et al., 2023). In engineering education, this should be taken into account during instructional design if the aforementioned projections are voiced in class, for example via emphasising representational literacy (Bainbridge et al., 2021).

Each strategy below is designed both to build the skills of the triad and to dismantle the affective barriers that prevent students from engaging with them.

3.1 Low-stakes sketching and iterative prototyping

Rationale

This strategy counters perfectionism and avoidance by making the iterative process, not the polished product, the explicit goal of visual-spatial tasks. Short, low-stakes exercises reduce emotional risk, encourage engagement without the paralysis of perfectionism, and embody a growth-oriented approach; for example, emphasising the quantity of sketches demonstrates that the skill can be built through practice (Johri & Lohani, 2011; Yang & Cham, 2007), and is not innate.

Practical implementation

Integrate short, focused sketching drills into your module using pen and unlined paper, as this discourages erasing and signals that generating multiple rough sketches is part of the work. Adapt exercises to discipline; for example, in structural or civil engineering, students might sketch a force-flow path through a truss node, whereas in mechanical or aerospace engineering, a quick isometric view of a bracket or flange may be drawn. Moreover, model your own thinking by narrating your reasoning, decisions, and corrections as you sketch. Your feedback should target the clarity of the engineering concept, not artistic quality, and peer review should be scaffolded with prompts such as: '*What relationship in this sketch is communicated clearly?*' or '*What question does this diagram suggest to you?*' This strategy builds spatial ability through mental manipulation, externalises visualisation for refinement, and practises the conventions of representational literacy in a low-risk environment. Table 2.9.1 summarises the dos and don'ts for efficiently implementing this strategy.

Table 2.9.1: Guidelines for low-stakes sketching and iterative prototyping

Do's	*Don'ts*
Use pen-based computing or pen and unlined paper and embrace iterative drafting.	Grade for neatness or penalise exploratory, messy sketches.
Frame sketching as engineering communication or visual thinking.	Allow for the '*I can't draw*' narrative to become an opt-out option.
Design activities with multiple valid solutions or representations.	Present a single correct sketch as the only goal.
Give feedback on logical clarity and engineering content.	Criticise early, rough drafts as wrong.
Model your own sketching process with a think-aloud narration that includes corrections.	Present solutions without co-construction or reasoning aloud.

Example 1. The foundational spatial skills programme at Michigan Tech

In the foundational spatial skills programme at Michigan Tech, students using multimedia software combined with guided workbook sketching showed significantly greater gains on the PSVT:R than those using software alone. The finding remained consistent across multiple cohorts and underpins the programme's core principle, that is, sketching 3D objects greatly enhances spatial skills (Sorby, 2009).

3.2 Physical and digital manipulatives for embodied learning

Rationale

Manipulatives ground abstract spatial transformations in tactile experience and real-time visual feedback. They reduce cognitive load by offloading mental work onto the physical environment, making spatial relationships concrete and observable. This approach provides compensatory pathways that are particularly valuable for students who find purely internal visualisation difficult.

Practical implementation

Begin with simple geometric solids to practise foundational mental rotation, then progress to authentic engineering components (valve bodies, linkage arms, printed circuit boards). Crucially, pair the physical act with a cognitive task; for example, after manipulating an object, have students sketch it from a new orientation or predict its cross-section. Then, use digital tools as complementary layers, such as augmented reality (AR) applications or sensor-embedded models that synchronise physical rotation with virtual display and powerfully demonstrate the connection between physical rotation of an object and its orthographic projections or internal structure/mechanics as it rotates (Fang et al., 2022; Gómez-Tone et al., 2022). For remote contexts, encourage household objects, like modelling clay and building blocks, for initial tactile exploration. Lastly, ground these tasks in engineering contexts, and frame each activity with clear reasoning questions such as '*How does the meshing (or the cross-section) of these gears change if I rotate this shaft?*'. This strategy strengthens spatial ability through embodied cognition, provides a concrete scaffold for visualisation, and allows students to test and verify mental manipulations externally. Table 2.9.2 summarises the do's and don'ts for efficiently implementing this strategy.

Table 2.9.2: Guidelines for physical and digital manipulatives for embodied learning

Do's	*Don'ts*
Pair physical manipulation with a follow-on task like a sketch or reasoning from a new viewpoint.	Use manipulatives without a clear analytical learning objective.
Progress from simple geometric shapes to authentic, industry-relevant components.	Rely solely on abstract shapes or disconnect activity from engineering contexts.
Use digital simulations to reveal hidden features (internal cutaways or force vectors) that physical objects cannot show.	Use digital simulations alone when a physical object would provide richer tactile and proprioceptive feedback.
Frame the manipulative as a valid external workspace and validate multiple pathways to understanding and externalising visual-spatial cognition.	Assume all students are building the same vivid internal image.

Example 2. Learning gains on the PSVT:R

In a controlled study with second-year engineering students, a group training with 3D-printed engineering components embedded with sensors, who visualised the physical rotation alongside a precisely rotated virtual model, achieved normalised learning gains of 41.2% on the PSVT:R after five weeks, compared to 8.2% for a control group. Gains increased when authentic engineering components were used in place of generic shapes, demonstrating that student motivation and interest are enhanced when spatial training is contextually meaningful (Fang et al., 2022).

Example 3. AR-supported spatial training sessions

In a study with first-year Civil Engineering students, an experimental group completed five two-hour, AR-supported spatial training sessions using a physical workbook, webcam, AR software, and fiducial markers (i.e., printed markers that the webcam can recognise, prompting the AR software to display the 3D model *associated with the 2D visual or exercise in the workbook). When the workbook markers were shown to the camera, students could visualise the corresponding 3D object, helping them move between orthographic drawings, spatial relationships, missing views, and hand-sketched 3D constructions. After the intervention, students showed significant gains on spatial ability tests, including the MRT, and achieved significantly higher final grades than the control group in Technical Drawing and CAD, Physics, Calculus, and Linear Algebra. The study demonstrates how AR can be used as a structured scaffold for repeatedly connecting 2D representation, 3D visualisation, and manual sketching in early engineering education (Gómez-Tone et al., 2022).*

3.3 Anonymous peer feedback to build confidence

Rationale

This strategy addresses performance anxiety and perfectionism by creating a psychologically safe environment for sharing preliminary work. Anonymity lowers the emotional risk of exposing imperfect sketches, and structured feedback protocols shift focus from the individual to the engineering content of the work produced. It teaches students to critique visual representations constructively, deepening their representational literacy while fostering a collaborative, growth-oriented culture and — an essential factor — disconnecting the work produced from the person(s) who produced it.

Practical implementation

Integrate regular, low-stakes opportunities for anonymous submission and critique. Peer assessment in higher education has been shown to improve academic outcomes (Double et al., 2020; Nicol et al., 2014), and anonymous peer review specifically can reduce evaluation apprehension and encourage candid engagement with visual work (Rotsaert et al., 2018; Vanderhoven et al., 2015). Use accessible tools (like shared digital whiteboards such as Miro, polling software such as Mentimeter) and pen-based or digital sharing tools (Johri & Lohani, 2011) to ensure anonymity is effortless and efficient in large classes. Begin with students anonymously submitting a draft solution (e.g., a force diagram, a conceptual sketch, a first attempt at a graph) and display submissions without attribution. Then, provide objective prompts to guide feedback; for example, ask: '*Identify one relationship communicated very clearly here*' or '*What one question does this sketch raise?*' You may also model this feedback language yourself and publicly celebrate insightful observations, reinforcing that the goal is collective understanding, not ranking or connecting a student's identity with the work produced. This ritual builds the habit of separating the creator from the creation, making critique a psychologically safe standard part of engineering practice.

This strategy primarily supports representational literacy by training students to analyse and critique visual communications for clarity and accuracy. By lowering anxiety and mitigating perfectionism, it enables more free engagement in the cognitive work of spatial and visual thinking and promotes constructive and psychologically safe, anxiety-free developmental learning.

Example 4. Pen-based computing system

Johri and Lohani (2011) implemented a pen-based computing system (Tablet PCs with DyKnow software) across Virginia Tech's first-year engineering module involving approximately 1500 students. Survey data from 525 students revealed that 73% agreed that the technology effectively contributed to their learning, specifically by moving them beyond passive copying to active, collaborative knowledge construction. The anonymous sharing feature was attempted to reduce student embarrassment and build confidence in the process of visual representation.

3.4 Structured concept mapping for visual synthesis

Rationale

Concept mapping develops representational literacy and combats cognitive rigidity by requiring students to actively structure knowledge and articulate relationships visually. The absence of a single correct map encourages cognitive flexibility, reduces anxiety about finding a single right answer, and makes implicit mental models explicit and open to refinement. A concept map becomes a visual plan of attack for tackling analytical problems, making the logical pathway explicit before calculations begin.

Practical implementation

Introduce concept maps as tools for synthesis and problem-solving planning, not just recall. Begin with a focused prompt such as '*map the key variables and governing principles for a closed thermodynamic system*', or '*visualise the relationship between concepts from last week's stress analysis module*'. Use concept mapping software (e.g., CMapTools, draw.io) or digital whiteboards that allow easy rearrangement; this emphasises the malleability of knowledge structures and lowers the barrier to iteration. The process works well across three phases: 1) guided co-construction of a master map in class, with you modelling linking phrases that encode engineering relationships (e.g., '*is resolved by*' rather than '*related to*'); 2) annotation of the master map for a specific problem, numbering calculation steps, and highlighting the critical path; and 3) adaptation to a novel problem, requiring students to modify their map to account for new variables and demonstrating genuine conceptual transfer. Facilitate a gallery walk for map comparison, where students defend their structural choices and question each other's connections.

This strategy primarily strengthens representational literacy by teaching students to create and interpret a formal diagrammatic system (i.e., nodes, links, propositions). It directly supports visualisation by forcing an active, relational organisation of concepts, which is the foundational mental model for effective problem solving. Table 2.9.3 summarises the dos and don'ts for efficiently implementing this strategy.

Table 2.9.3: Guidelines for structured concept mapping for visual synthesis

Do's	*Don'ts*
Frame mapping as a formative tool for organising thinking, not a summative test of facts.	Present a single correct map as the only goal.
Use software that allows easy rearrangement to encourage iterative structuring and exploration.	Grade based solely on the number of nodes or superficial features.
Have students compare and defend their map structures in small groups.	Dismiss a student's map structure without exploring their rationale.
Use mapping to visually integrate topics and reveal the conceptual big picture.	Use mapping only at the end of a topic as a static summary.
Encourage cross-links that represent complex or causal relationships.	Focus feedback only on hierarchical correctness at the expense of novel and innovative connections.

Example 5. Students' reported confidence in engineering skills

In a sophomore Continuum Mechanics module at Smith College, USA, Ellis et al. (2004) embedded two concept maps throughout the curriculum: a module-level map relating material, geometry, loading, force, and stress, and a focused dynamics map for rigid-body problem solving. Across the semester, students' self-reported confidence in their engineering skills rose from 11% pre- to 81% post-intervention (n = 27). Concept maps were one of several pedagogical practices contributing to this gain, and students described the maps in focus groups as helping them see 'the big picture'.

3.5 Dedicated spatial skills module for intensive intervention

Rationale

For institutions with sufficient resources, a dedicated module provides the most structured pathway for building foundational spatial competencies (Porat & Ceobanu, 2024; Sorby, 2009). It creates a focused space where spatial thinking is the sole objective, enabling systematic Core Triad skill progression without the simultaneous pressure of complex engineering content. This approach is particularly effective as an equity intervention, as it provides intensive foundational support before students encounter failure in core curriculum modules, functioning as an academic catalyst.

Practical implementation

Begin with a validated diagnostic (e.g., using the PSVT:R) in the first week of a linked gateway module (e.g., Engineering Graphics), framed positively as an opportunity to identify areas for foundational development. Invite students scoring below a set threshold to enrol, framing this clearly as a meaningful investment, not a remedial placement. Structure the curriculum around deliberate skill progression from 2D to 3D thinking (i.e., transitioning from multi-view projections to auxiliary views, to mental rotation, to cross-sections), using hands-on sketching and physical model work as primary activities (e.g., sketching or physical model manipulations), with CAD or AR software as a complementary reinforcement layer once manual skills are established. Continually connect exercises to authentic engineering contexts (such as real component drawings, assembly sequences, and industry-relevant tasks) to maintain relevance and motivation.

Table 2.9.4: Ten-week spatial skills module

Module focus	*Key activity*	*Skills targeted*	*Deliverable*
Weeks 1-2 2D-3D translation	Isometric sketching from coded plans, and orthographic projection of simple blocks.	Spatial visualisation and mental projection.	Set of five isometric and orthographic sketch pairs.
Weeks 3-4 Surface and solid manipulation	Sketching cross-sections, surfaces of revolution, combining primitives.	Mental rotation and spatial relations.	Cross-section drawings of combined solids.
Weeks 5-6 Folding and pattern development	Paper-folding exercises; unfolding 3D objects to 2D nets.	Mental folding and spatial transformation.	Completed workbook exercises.
Weeks 7-8 Connecting to CAD	Recreating hand-sketched objects in basic CAD software.	Reinforcing mental models through digital representation.	Simple 3D CAD model files.
Week 9 Applied engineering context	Sketching and modelling a multi-part assembly (e.g., flange coupling or gear assembly).	Integrated visualisation and representational literacy.	Assembly sketch and basic CAD assembly.
Week 10 Review and post-assessment	Final skills review; re-administer diagnostic.	Measure growth and reinforce mastery.	Post-test score and final portfolio submission.

This strategy builds all three elements of the triad systematically, establishing foundational spatial ability, deliberate visualisation processes, and fluent representational literacy as core curriculum. Table 2.9.4 outlines a ten-week progression that implements this approach.

Example 6. Interventions for low-scoring students

Michigan Tech's required module for students scoring below the PSVT:R threshold uses sequenced activities in sketching, projection, and rotations (Sorby, 2009). Across cohorts, the intervention has produced substantial PSVT:R gains and acted as an equity intervention: retention was higher among women who enrolled in the module than among those who did not, at 76.7% compared with 47.8%, respectively (Sorby, 2009); this is noteworthy, as women are almost three times as likely as men to score below the threshold (Sorby et al., 2013). Other students who had taken part in similar interventions subsequently also performed significantly better in gateway modules, including Calculus (Sorby et al., 2013). These examples demonstrate how such interventions are effective for engineering students in general, and for women engineering students in particular, supporting the strategy of inclusion and equity discussed in Section 2.3.

4 Recommendations for implementations and learning

The five strategies described above form a tiered model for action. Their effectiveness, however, depends on the broader teaching environment in which they operate. Table 2.9.5 synthesises the core pedagogical shifts required, replacing environments that inadvertently reinforce anxiety and fixed-mindset thinking with those that deliberately foster growth, flexibility, and psychological safety.

Beyond this cultural foundation, four practical recommendations apply across all five strategies. First, use a validated diagnostic assessment (e.g., PSVT:R) at the outset of a module to identify students who would benefit most from foundational support, and/or diagnose where (within the Core Triad skillset cycle) students may be struggling; then use post-intervention assessment to measure growth and validate the intervention. Second, sequence from concrete to abstract (or vice versa) in all activities; begin with physical or hands-on manipulation before moving to digital or purely mental tasks. Third, connect every exercise explicitly to engineering outcomes to make the professional relevance of each spatial task visible to students before they begin, and resist treating any exercise as a warm-up that needs no justification. Fourth, collect longitudinal data in higher-level modules to validate the impact of any intervention, refine the approach over time, and build an institutional case for continued investment.

Finally, in addition to referenced literature in this chapter, we recommend Newcombe (2017), Sorby (2011), Sorby and Panther (2020) and Wang et al. (2025) for those of you who want to deepen their knowledge further.

Table 2.9.5: Teaching practices for fostering a growth mindset in visual-spatial learning

Do's	*Don'ts*
Frame challenges as skill-building and as cognitive workouts.	Praise innate talent (i.e., use language like '*you're a natural*') instead of effort and strategy.
Normalise struggle and iteration and share your own early drafts and corrections as an educator.	Expect perfect first drafts that validate perfectionism and penalise the exploratory work that is vital for learning.
Focus feedback on process and progress and comment on the improvement from first to second sketch.	Grade only the final product's neatness, since this incentivises hiding the learning process.
Offer different ways to demonstrate understanding (for example, a sketch, a physical model, or a verbal description).	Present only one correct visual solution; discourage messy creative problem solving.
Use low-stakes, frequent practice integrated throughout the module.	Rely on one high-stakes assessment, since this turns it into a test of fixed ability rather than a developing skill.

5 Concluding summary

This chapter has presented visual-spatial thinking as a central, trainable competency in engineering education, structured around the interdependent Core Triad of spatial ability, visualisation, and representational literacy. The evidence reviewed establishes that these skills are not innate characteristics, but a dynamic foundation that structured instruction can develop in all students, and that doing so is both an educational imperative and a meaningful equity strategy.

Implementing this vision requires a cultural shift, from assuming visual fluency to deliberately building it. The five strategies outlined in Section 3, from low-stakes sketching to dedicated spatial modules, provide a practical toolkit for educators to implement in their classrooms. The teaching mindset synthesised in Section 4 provides the conditions under which those tools are most effective. Together, they support educators in cultivating engineers who are not only proficient analysts but fluent spatial-visual thinkers, and designers who translate mental models into reality, problem solvers who see system behaviour before it is built, and collaborators who communicate complex ideas with precision. By deliberately making the implicit explicit, engineering educators can build an inclusive foundation for the innovative solutions the future demands.

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AI statement

During the preparation of this work, the authors used Claude and ChatGPT in order to check and correct grammatical errors, punctuation, and/or improve sentence clarity. After using this tool, the authors reviewed, edited, and made the content their own as needed. They take full responsibility for the content of the publication.

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