Doctoral Thesis in Technology and Learning

Bridging Policy and Practice in Spatial Ability Development

A Curriculum and Teaching Inquiry

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KTH ROYAL INSTITUTE OF TECHNOLOGY

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Abstract

A curriculum is a complex system shaped by educational values, institutional structures, and policy priorities. Within these systems at the compulsory level, spatial ability—the mental capacity to visualise, manipulate, and transform visual-spatial information—is inconsistently addressed, which translates to inconsistencies in classroom practice as well. While research increasingly acknowledges its significance, spatial ability is rarely positioned as an explicit learning goal within national curricula. Its development is often left to implicit interpretation, creating systemic ambiguity that affects equitable access to spatial ability development opportunities, particularly during the foundational years of schooling.

This thesis investigates how spatial ability development is positioned at the intersection of curriculum policy and teaching practice, with a specific focus on primary and lower secondary education in Sweden. The central research question is: How is the development of spatial ability situated within the national curriculum and supported through educational practice? Sub-questions explore how spatial ability is represented and structured in curriculum documents, and how teachers perceive and implement its role within their teaching.

Framed by Bronfenbrenner's ecological systems theory, which situates human development within interacting layers from policy to classroom practice, the study explores how these levels shape spatial ability development. Guided by an interpretivist paradigm, it adopts a qualitative, multi-method design incorporating grounded theory and a phenomenological approach. The research is primarily situated in the Swedish education system, with Ireland

serving as a secondary, comparative context. The thesis comprises five interlinked papers, collectively exploring curriculum and teaching from both systemic and practitioner perspectives. Paper A establishes a foundational understanding of system-level enablers and barriers that influence spatial ability development. Paper B focuses on how spatial ability is embedded in Swedish Technology and Craft education. Paper C develops a structured analytical framework to evaluate curriculum representation. Paper D extends this analysis across the broader Swedish national curriculum beyond Technology and Craft. Finally, Paper E brings in teacher perspectives, contextualising curriculum findings within classroom practice and comparing implementation between Sweden and Ireland.

Findings are interpreted through Bronfenbrenner's ecological systems model. At the macrosystem level, national curricula in both Sweden and Ireland do not explicitly define spatial ability as a learning objective, limiting coherent policy support. At the mesosystem and exosystem levels, subject organisation, interdisciplinary structures, and assessment frameworks shape whether and how opportunities for spatial ability development are constructed within curriculum pathways. At the microsystem level, teachers consistently acknowledge the value of spatial ability and attempt to integrate it into their practice. However, such efforts remain informal, uncoordinated, and dependent on individual initiative, resulting in uneven experiences for learners.

This thesis reveals a disconnect between curriculum policy and classroom practice, where the development of spatial ability depends heavily on teacher agency in the absence of systemic support. The thesis argues that bridging this gap requires more intentional integration of spatial ability into curriculum frameworks, alongside institutional supports that align policy, practice, and pedagogy. In doing so, it contributes to broader discussions on how national education systems can better support foundational cognitive development through both policy and practice.

Keywords
Spatial ability, National curriculum, Ecological systems theory, Interpretivism, Compulsory education.

Sammanfattning

Läroplanen består av flera policydokument som tillsammans bildar ett komplext system, format av utbildningsideal, institutionella strukturer och politiska prioriteringar. Inom detta system behandlas spatial förmåga – det vill säga förmågan att mentalt visualisera, manipulera och omforma visuospatial information – på ett inkonsekvent sätt vilket också speglas i klassrumspraktiken. Trots ett växande forskningsstöd för spatial förmågans betydelse, är den sällan formulerad som ett explicit lärandemål i de nationella styrdokumenten. Ansvar för undervisningen lämnas i stor utsträckning till lärarens tolkning av kursplanen, vilket riskerar att skapa en ojämlik undervisningspraxis där vissa elever ges möjlighet att utveckla denna förmåga i skolan – medan andra inte ges den möjligheten. Denna variation är särskilt problematisk i de tidiga skolåren, då grunden för kognitiv utveckling läggs.

Denna avhandling undersöker hur spatial förmåga positioneras i skärningspunkten mellan utbildningspolitik och pedagogisk praktik, med särskilt fokus på de tidiga skolåren i svensk grundskola, det vill säga låg- och mellanstadiet. Den övergripande forskningsfrågan lyder: Hur är utvecklingen av spatial förmåga situerad i den nationella läroplanen, och hur stödjs den i den praktiska undervisningen? Avhandlingen bygger på delstudier som dels analyserar hur spatial förmåga formuleras och representeras i läroplansdokument, dels belyser hur lärare uppfattar dess betydelse och integrerar den i sin undervisning.

Studien är teoretiskt förankrad i Bronfenbrenners ekologiska systemteori, som förstås som en modell där mänsklig utveckling formas genom interaktioner mellan flera ömsesidigt påverkande nivåer – från utbildningspolitik till

klassrumspraktik. Forskningsansatsen är interpretativ och bygger på en kvalitativ, blandad forskningsdesign med metodologiska inslag av både grounded theory och fenomenologi. Forskningen är huvudsakligen förlagd till det svenska utbildningssystemet, med Irland som ett jämförande kontext för att belysa likheter och skillnader i läroplansutformning och undervisningspraktik.

Avhandlingen består av fem sammanlänkade artiklar som undersöker läroplanen och undervisningen utifrån både ett system- och praktikperspektiv. Artikel A ger en grundläggande förståelse för strukturella möjligheter och hinder som påverkar undervisningen kring spatial förmåga. Artikel B fokuserar på hur utveckling av spatial förmåga är integrerad i den svenska teknikundervisningen. Vidare utvecklar artikel C ett analytiskt ramverk för att utvärdera hur spatial förmåga integreras i läroplanen. Artikel D breddar sedan analysen till att omfatta hela den svenska nationella läroplanen utöver teknikämnet. Slutligen tillför artikel E ett lärarperspektiv som kontextualiserar läroplansstudierna i en klassrumspraktik och jämför hur detta görs i en svensk respektive irländsk kontext.

Resultaten tolkas med stöd av Bronfenbrenners ekologiska systemmodell. På makrosystemnivå visar studien att läroplanerna i både Sverige och Irland saknar tydlighet kring utvecklingen av spatial förmåga som ett uttalat lärandemål. Detta begränsar möjligheterna till en samordnad och målinriktad policy inom respektive utbildningssystem. På exo- och mesosystemnivå påverkar faktorer som ämnesstruktur, ämnesövergripande organisering och bedömningspraxis i vilken utsträckning undervisningen faktiskt skapar utrymme för utveckling av elevers spatiala förmåga. På mikrosystemnivå framhåller lärare vikten av spatial förmåga och försöker därför integrera träning av denna i sin undervisning. Dessa insatser är dock ofta informella, osystematiska och beroende av enskilda individers engagemang, vilket leder till ojämna elevupplevelser och en bristande likvärdighet i undervisningen.

Avhandlingen synliggör därmed glapp mellan önskad effekt, policy och klassrumspraktik, där utvecklingen av spatial förmåga i hög grad vilar på lärarens eget initiativ i frånvaro av systematiskt stöd. För att överbrygga dessa glapp argumenterar avhandlingen för en tydligare och mer medveten integrering av spatial förmåga i läroplanen, i kombination med institutionellt stöd som samordnar policy, praktik och pedagogik. På så sätt bidrar studien till en bredare diskussion om hur nationella utbildningssystem kan främja

grundläggande kognitiv utveckling genom både policyutformning och undervisningspraktik.

Nyckelord
Spatial förmåga, Rumslig förmåga, Nationell läroplan, Ekologisk systemteori, Interpretivism, Obligatorisk utbildning.

Acknowledgments

The journey has come to an end sooner than I expected. Growing up in the south, snow was always a fantasy for me. I'm incredibly grateful to have landed in this beautiful country, which has left a bold, unforgettable stroke on the canvas of my life.

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KTH. I entered the program stronger in quantitative methods, but now I can proudly say I'm comfortable with both. You've always understood exactly what I needed and gave timely, precise feedback, something I never took for granted. Your wide-ranging expertise beyond technology education also encouraged me to explore, expand, and evolve.

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List of publications

Paper A: Bufasi, E., Lin, T. J., Benedicic, U., Westerhof, M., Mishra, R., Namsone, D., et al. (2024). Addressing the complexity of spatial teaching: A narrative review of barriers and enablers. *Frontiers in Education*, *9*, 1306189. https://doi.org/10.3389/feduc.2024.1306189

Paper B: Lin, T. J., Buckley, J., Gumaelius, L., & Ampadu, E. (2023). Situating spatial ability development in the Craft and Technology curricula of Swedish compulsory education. *The 40th International Pupils' Attitudes Towards Technology Conference Proceedings 2023*, 1(October).

Paper C: Lin, T. J., Buckley, J., Gumaelius, L., & Ampadu, E. (2024). The potential for spatial ability development through the Swedish technology and craft compulsory curricula. *International Journal of Technology and Design Education*, 1-19. https://doi.org/10.1007/s10798-024-09958-7

Paper D: Lin, T. J., Buckley, J., Gumaelius, L., & Ampadu, E. (2024). Locating the potential development of spatial ability in the Swedish national curriculum. *Heliyon, 10*(19). https://doi.org/10.1016/j.heliyon.2024.e38356

Paper E: Lin, T. J., Gumaelius, L., Buckley, J., & Ampadu, E. (Under Review). How do teachers develop spatial ability within the national curriculum? A phenomenological study of Ireland and Sweden.

Scientific papers not included in the thesis

Alongside the five primary publications that form the core of this thesis, a complementary piece of related work was developed to support readers in understanding how the research insights can be translated into practical actions for educators and stakeholders. While not discussed within the thesis, it serves as a parallel output to help practitioners apply research-based strategies aligned with the thesis themes:

> Malkogeorgou, S., & Lin, T. J. (2024). Empowering minds: A spatial curriculum for academic brilliance. In R. M. Klapwijk & G. Duffy (Eds.), Making SPACE for spatial thinking in STEAM education: Teacher professional development modules (pp. 104-117). Technological University Dublin. https://arrow.tudublin.ie/engschelebk/23

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1. Introduction

"The eye sees only what the mind is prepared to comprehend." — Robertson Davies, 1951.

While Davies may have used this expression metaphorically to suggest that human perception of the world is shaped by knowledge and expectation, his words align with a fundamental principle of cognitive science: perception is not a passive reflection of external reality, but an interpretation constructed by the mind. Our ability to make sense of what we physically see depends not only on sensory input, but also on how our minds are conditioned (Baddeley, 1992; Flanagan & McDonough, 2018). Whether navigating environments or predicting an object's movement, our understanding of physical space is actively shaped by cognitive frameworks and learned experiences (Hambrick et al., 2012; Newcombe & Shipley, 2014; Peer et al., 2021).

1.1. Core Terminology and Structural Outline

The cognitive capacity described above is commonly referred to as spatial ability. Throughout this thesis, the term spatial ability will be used consistently, following the most contemporary framework of cognitive factors, which defines it as "the ability to make use of simulated mental imagery to solve problems—perceiving, discriminating, manipulating, and recalling non-linguistic images in the 'mind's eye'" (Schneider & McGrew, 2018, p.125)

While spatial cognition, spatial reasoning, spatial thinking, spatial skill, spatial visualisation, and spatial ability are often used interchangeably in the literature, this thesis adopts spatial ability as its central concept. This choice is made for clarity and precision. Spatial ability refers to a measurable cognitive

capacity that includes visualisation, transformation, orientation, and mental manipulation (Buckley et al., 2018; Lohman, 1993; Soluki et al., 2021; Wai et al., 2009). It serves as a suitable anchor point for this thesis because it encompasses core visuospatial competencies yet is specific enough to allow consistent measurement in research.

To avoid conceptual overlap, the following related terms are described and distinguished:

- Spatial cognition refers to the broad mental processes involved in perceiving, encoding, storing, and manipulating spatial information. It includes attention, memory, and problem-solving (Judd & Klingberg, 2021; Malanchini et al., 2020). Although highly relevant, its expansive scope exceeds the focus of this thesis.
- Spatial reasoning refers to logical thinking applied to interpreting spatial relationships. It often occurs in structured problem-solving settings, involving inference and analogical reasoning (Kamath et al., 2023). It is a specific dimension of spatial cognition that emphasises reasoning processes.
- Spatial thinking encompasses spatial concepts, representational tools (e.g., diagrams, maps), and reasoning strategies. One of the defining characteristics of spatial thinking is its context-dependence. It may vary across disciplines, and transferring it from one domain to another is neither automatic nor straightforward. While reasoning is a component of thinking, the latter reflects a more comprehensive integration of cognitive processes—extending beyond reasoning—within specific learning environments.
- Spatial skill often denotes a trainable and task-specific competency shaped by experience or instruction (Uttal et al., 2013). Although closely related, spatial ability is generally considered a more stable trait, influenced by both innate factors and developmental contexts (Hawes & Ansari, 2020; Tzuriel & Egozi, 2010; Wai et al., 2009). While spatial ability can also be improved through training, it reflects a broader underlying capacity rather than isolated task performance.
- Spatial visualisation is a narrower subcomponent of spatial ability, involving mental manipulation of 2D and 3D objects. Spatial ability, in turn, includes additional processes such as perspective-taking and spatial orientation (Buckley et al., 2018; Maeda et al., 2013; Mix et al., 2018; Miyake et al., 2001; Sorby et al., 2018a).

While these constructs overlap and are sometimes used interchangeably, this thesis prioritises spatial ability for its balance between conceptual breadth and analytical precision. It represents a foundational cognitive capacity applicable across contexts, without being tied to domain-specific tools, learned tasks, or situational reasoning. This focus is particularly appropriate, as the thesis does not examine individual performance, but rather aims to develop a general understanding of how spatial ability is perceived and discussed in educational discourse.

To ensure clarity and conceptual coherence, this thesis adopts a tiered approach to the use of terminology. Core theoretical constructs that are central to the argument are defined in the main text upon first mention. Terms that are context-dependent, policy-specific, or culturally situated but not conceptually complex are briefly clarified in footnotes. Technical or specialised terms that are relevant and used recurrently, yet not central to the core argument, are compiled in the glossary (Appendix A) for reference.

The thesis is organised into six sections:

1. Introduction: This section introduces the core terminology, outlines the overall structure of the thesis, presents the motivation for the study, and states the research questions that guide the investigation.
2. Background and Foundations: This section offers an in-depth exploration of the development of spatial ability literature over time, specifically addressing ontological and epistemological considerations that justify the philosophical stance underpinning this thesis.
3. Methodology: This section provides a detailed account of the methodological approaches applied in the appended papers. It also addresses issues of trustworthiness and ethical considerations relevant to the research process.
4. Results and Discussion: The results of the appended papers are presented and interpreted through the lens of Bronfenbrenner's (1976, 1979) ecological systems theory. Rather than discussing each paper individually, this section integrates the findings across the papers, highlighting how they collectively address the research questions through triangulation. Limitations of the thesis are discussed, and directions for future research are proposed.
5. Contribution to Knowledge: This chapter provides a concise synthesis of the principal findings and insights, presenting the contribution to the field of knowledge under discussion.

6. Conclusion: The final section reflects on the thesis and provides concluding remarks.

1.2. Research Motivation

1.2.1. Why Spatial Ability Matters?

Spatial ability plays a fundamental role in everyday problem-solving tasks, from interpreting maps and following directions to arranging furniture (Lane & Sorby, 2022). Recognised as a key component of human intelligence (Buckley et al., 2018; Lohman, 1993; McGrew, 2023; Schneider & McGrew, 2018), spatial ability has been closely associated with academic achievement, particularly in Science, Technology, Engineering, and Mathematics (STEM) education (Castellar & Juliasz, 2018; Sorby et al., 2018a). In this thesis, STEM education is used as an umbrella term encompassing Science, Technology, Engineering, and Mathematics, along with related disciplines. It refers to formal educational contexts where these subjects are taught, including interdisciplinary approaches that integrate STEM concepts across broader curricular frameworks. Success in these fields often depends on the ability to process and manipulate spatial information. For instance, in Mathematics, students must visualise and mentally combine objects to count the sides of two-dimensional shapes (Nguyen et al., 2016). Similarly, in Science, hands-on experiments require visual-motor coordination, enabling students to perform precise physical tasks such as using mobile devices (Wang et al., 2017).

Beyond STEM disciplines, spatial ability also influences learning in other non-STEM areas. In this thesis, non-STEM refers to academic disciplines outside Science, Technology, Engineering, and Mathematics. It includes formal education contexts such as the Humanities, Social Sciences, and the Arts, as well as interdisciplinary approaches that integrate non-STEM content into broader curricula. In language acquisition, for instance, skills such as visualisation and form constancy help students recognise letters and words in various fonts and printed materials, such as posters or textbooks (Posamentier et al., 2021). Likewise, in music education, particularly when learning to play instruments, students develop pattern recognition as they match musical notation to corresponding positions on their instruments (Forgeard et al., 2008).

Research suggests that spatial ability is not solely an innate trait but can be strengthened through explicit training and structured learning experiences (Atit et al., 2020; Hambrick et al., 2012; Malanchini et al., 2020; Uttal et al., 2013). Without such spatial training, domains of reasoning, including problem-solving and everyday decision-making, may remain inaccessible to many learners (Buckley et al., 2018; Judd & Klingberg, 2021; Sorby et al., 2018a; Wai et al., 2009). Despite its well-documented importance, spatial ability development for students remains underexplored in the national education systems worldwide (Lin et al., 2024a, 2024b). In this thesis, national education refers to a formal education system governed by a country's policies, standards, and curricula, designed to align with national educational goals, cultural values, and societal needs. It typically includes primary and secondary education under a standardised framework set by government authorities or education ministries.

Currently, there are two primary approaches to spatial ability development: isolated and embedded (Newcombe, 2017). Isolated interventions involve structured training programs designed separately from the formal curriculum, often developed by researchers and implemented in classrooms as discrete activities, such as Sorby's spatial training program, which has demonstrated moderate effects on spatial ability (Sorby, 1999, 2009). In addition, most isolated interventions in existing research focus on extracurricular programs[1], specialised STEM tracks[2], or enrichment activities[3] (Lin et al., 2024a; Uttal et al., 2013). Relying heavily on informal learning and extracurricular activities might create unequal opportunities, which might further lead to performance gaps due to socio-cultural influences, educational access, and curriculum design (Bufasi et al., 2024; Sorby et al., 2018a; Yilmaz, 2009).

For instance, social norms and gender expectations could influence childhood experience, with boys often encouraged to engage in activities that expose

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[1] **Extracurricular programs:** Educational activities outside the formal curriculum, such as clubs, competitions, or workshops, that provide additional learning opportunities.
[2] **STEM tracks:** Specialised academic pathways within formal education that focus on STEM subjects, often including advanced coursework, hands-on projects, and career-focused training.
[3] **Enrichment activities:** Supplementary learning experiences beyond the formal curriculum, often optional or advanced. Examples include competitions, workshops, research programs, after-school clubs, and mentorships. These hands-on opportunities enhance skills but may not be equally accessible to all students.

them more to spatial ability, such as playing with construction toys (Yilmaz, 2009). Additionally, students from lower socioeconomic backgrounds and underrepresented groups in STEM often have fewer opportunities to develop spatial ability, as spatial training is rarely emphasised in pre-college education (Sorby et al., 2018). Furthermore, curriculum limitations fail to address the needs of spatially talented[4] learners, preventing them from fully developing their potential, thereby widening the spatial ability gap (Bufasi et al., 2024). In contrast, embedded interventions integrate spatial ability development directly into regular teaching practices, such as sketching, gesturing, and diagram use, without increasing instruction time to the formal curriculum. This approach, referred to as spatialising the curriculum by Newcombe (2017), is particularly relevant in STEM education, where spatial ability is often inherently required.

In contrast, the embedded approach is implied in many national curricula—the written document established by a government or education authority that outlines learning objectives, subject content, and assessment standards for formal education. They assume that spatial ability naturally emerges as a byproduct of general STEM education rather than requiring explicit instruction (Lin et al., 2024a; Newcombe, 2017; Uttal & Cohen, 2012). It is necessary to examine how spatial ability can be integrated into national curricula. Such integration is essential for improving equitable access to opportunities for spatial ability development for the majority of students.

1.2.2. Why Curriculum Matters?

A few countries have introduced targeted initiatives to formally incorporate spatial ability into their educational systems. In the United States, the National Research Council's *Learning to Think Spatially* underscored the need to develop spatial ability across K–12 education and to prepare teachers for its instruction and assessment (National Research Council, 2006). In the United Kingdom, a toolkit developed by Bates et al. (2023) supports the integration of spatial ability into the country's early Mathematics education. Similarly, Ireland has launched a national initiative that collected baseline data on first-year secondary students' spatial ability to guide curriculum reform and embed spatial training (Bowe et al., 2016). At the European level, the Spatially

[4] **Spatially talented:** Young individuals with exceptional spatial ability, demonstrating advanced visualisation, mental rotation, and spatial reasoning skills beyond their peers.

Enhanced Learning Linked to STEM (SellSTEM) project spans eight countries, aiming to strengthen STEM education by identifying systemic enablers and barriers to spatial ability development, informing educational policy, and enhancing teacher training (European Commission, 2024).

Studying through the national curriculum offers a grounded perspective for understanding educational objectives and broader societal priorities. As Dewey (2024) argued, education should foster both individual growth and social development. Rooted in a nation's cultural, political, and social contexts, the national curriculum reflects prevailing values and educational aims (Yates & Grumet, 2011). Engaging with it enables students and educators to connect learning to broader social narratives, thereby supporting cognitive and civic development. The national curriculum also serves as a platform for stakeholder agency. Students are playing a growing role in curriculum design. Their involvement helps ensure that educational content remains relevant and responsive to their lived experiences (Manyukhina & Wyse, 2019). Also, from a social justice perspective, the national curriculum plays a central role in promoting equity. As the most structured and widely accessible educational framework, it defines comprehensive learning objectives for the majority, shaping academic achievement and social mobility (Van Den Akker et al., 2003; Yates & Grumet, 2011). The economic dimension further reinforces the relevance of the national curriculum. As curricula increasingly align with workforce demands, particularly in STEM field, the national curriculum reflects broader economic trends and national strategies (Slattery, 2024; Smith & White, 2024). It functions as a policy tool that prepares learners for participation in a rapidly evolving, technology-driven labour market. Ultimately, examining any subject through the national curriculum provides a valuable means of tracing educational change and evaluating how education remains relevant in an increasingly complex world.

1.3. Research Contexts

This thesis focuses on primary and lower secondary contexts for several interconnected reasons. First, these levels represent the foundation of compulsory education in most national systems, ensuring that the curriculum at this stage reaches the broadest and most diverse population of students. Second, these years are critical for spatial ability development, as research indicates that early and sustained engagement with spatial ability tasks significantly enhances later academic achievement, particularly in STEM-

related domains (Lauer & Lourenco, 2016; Verdine et al., 2017; Zhang et al., 2014). Moreover, focusing on these stages supports equity in education, as relying on upper-secondary electives or extracurricular programs to develop spatial ability risks reinforcing existing disparities tied to socioeconomic background, gender, and access to resources (e.g., Sorby et al., 2018).

This thesis draws on two national systems—Sweden and Ireland—within the broader context of the EU-funded SellSTEM project[5], which included additional partner countries such as the Netherlands and Latvia. These countries contributed to system-level comparisons in Paper A, particularly in identifying enablers and barriers to spatial ability development across Europe. However, they are not included in this thesis's core analysis for two main reasons. First, the official curriculum documents from the Netherlands and Latvia are primarily published in Dutch and Latvian, respectively, without full, authoritative English translations. This poses a risk of interpretive bias when conducting nuanced curriculum analysis across linguistic boundaries. Second, this thesis prioritises depth over breadth, focusing on two education systems that allow for both rigorous curriculum comparison and access to relevant practitioner perspectives.

Sweden's compulsory education system, known as grundskolan, spans ten years of formal schooling. It begins with kindergarten (förskoleklassen) at age six, followed by compulsory schooling from Years 1 through 9, or their equivalent (Skolverket, 2025). The system is publicly funded and centrally overseen by the Swedish National Agency for Education (Skolverket), which sets curriculum goals and assessment frameworks. While the curriculum provides national consistency, it also grants teachers substantial autonomy in how content is interpreted and delivered. Emphasising equity, democratic values, and student responsibility, the curriculum promotes formative assessment in early years and introduces summative grading from Year 6. Core subjects such as Mathematics, Swedish, Science, and Social Studies are taught alongside Technology and Craft, supporting a holistic and interdisciplinary learning approach (Skolverket, 2024).

[5] **The EU-funded SellSTEM project** (Marie Skłodowska-Curie Innovative Training Network) is acknowledged in the Acknowledgements section of this thesis for its support in advancing research on spatial ability in STEM education.

Ireland's compulsory education is structured in two main stages: primary and post-primary (encompassing both lower and upper secondary levels). Primary education is compulsory from age six to approximately twelve. It is followed by post-primary education, which begins with a three-year lower secondary cycle known as the Junior Cycle (Years 1–3), typically covering ages twelve to fifteen. The Department of Education centrally administers the curriculum and assessment frameworks. At the primary level, the curriculum focuses on cognitive, emotional, and physical development through subjects including Languages, Mathematics, Arts education, and Social and Environmental Studies. The Junior Cycle builds on this foundation through a national framework that emphasises active learning, key skills, and a balance of formative and summative assessment. It also foregrounds student well-being, cross-curricular integration, and project-based learning. Both stages are publicly funded, and recent reforms have placed equity, inclusion, and learner voice at the centre of national policy.

These two systems differ notably in how they approach spatial ability development within education. Ireland adopts an outcome-oriented and exam-focused model, embedding spatial tasks into Mathematics instruction (Gleeson, 2022; National Council for Curriculum and Assessment, 2017). In contrast, Sweden reflects a tradition of pedagogical flexibility and grants teachers substantial curricular autonomy, enabling them to decide how spatial ability is addressed in practice (Bladh, 2020; Pettersson et al., 2015). These distinctions provide a meaningful context for understanding the broader curriculum-policy-practice relationships examined throughout this thesis.

1.4. Research Questions

The thesis offers insights into how spatial ability can be embedded within educational systems to support its development among students. To frame this inquiry, Bronfenbrenner's ecological systems theory (1976, 1979) is employed to analyse the dynamic interplay between curriculum policy, institutional frameworks, teacher practices, and classroom pedagogy. Rather than viewing learning as an isolated cognitive process, this theoretical approach situates it within a network of interrelated influences (Anderson et al., 2014; Bronfenbrenner, 1976, 1979; Bronfenbrenner & Morris, 2007, 2007; Neal & Neal, 2013). It highlights that the development of spatial ability is shaped not only by individual aptitude but also by systemic and environmental factors. Within this framework, the thesis consolidates Bronfenbrenner's levels of

systems into two key perspectives that guide the subsequent discussion, which is the curriculum perspective and the teaching perspective.

Accordingly, the central research question guiding this thesis is:

How is the development of spatial ability situated within the national curriculum and supported through educational practice?

This overarching question is further refined into the following sub-research questions:

1. How is spatial ability represented and structured within the Swedish national curriculum?

2. How do teachers perceive and implement the role of spatial ability within the national curriculum?

1.5. Structure of Included Papers, Authorship Roles, and Publication Strategy

1.5.1. Structure of Included Papers

This thesis follows a structured progression, with each paper building upon the previous to form a cohesive narrative.

Paper A establishes the foundational understanding of systemic enablers and barriers to developing spatial ability for students, framing the broader context. Paper B narrows the focus to the Swedish curriculum, identifying how spatial ability is embedded within Technology education. Paper C refines this analysis by introducing a structured framework for evaluating the curriculum. Paper D expands the scope further, applying this framework across the entire Swedish national curriculum beyond Technology education. Paper E integrates teacher perspectives, contextualising the findings within pedagogical practice and comparing curriculum implementation across two countries.

Papers B, C, and D address the research questions from a curriculum perspective, while Paper E addresses them from a teaching perspective. Collectively, these studies connect curriculum policy, institutional frameworks, teacher practices, and classroom pedagogy, converging on the overarching

theme of spatial ability development within the national curriculum. Figure 1 illustrates the relationships among the papers.

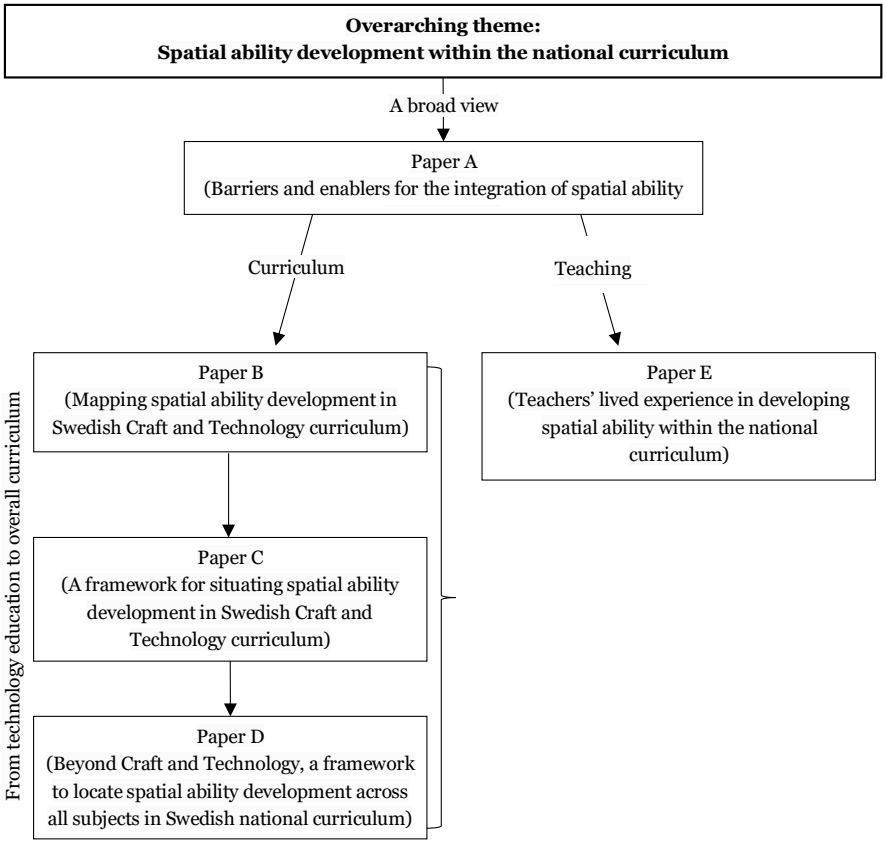

Figure 1:Structure of Included Papers.

1.5.2. Authorship Roles

The author of this thesis served as the lead author on Papers B-E and the second author in Paper A. Table 1 specifies the roles of the author of this thesis and the supervisors across all papers to ensure transparency.

Table 1:Authorship roles across papers.

Papers	Author of the thesis	Supervisors
Paper A Peer-reviewed journal article	1. Data collection: Conducted a structured literature review using academic databases. 2. Data curation: Organised and systematised qualitative data from curriculum and pedagogical documents. 3. Formal analysis: Analysed cross-national curriculum content and interpreted thematic patterns. 4. Investigation: Identified relevant education policies and instructional practices across contexts. 5. Writing: Authored section "4.2 From a review of the selected curricula, what barriers and enablers are structurally apparent with respect to curriculum organization?" and contributed to the overall review and refinement of the manuscript.	1. Validation: Supported the verification of analytical approaches, interpretation of findings, and theoretical alignment. 2. Supervision: Offered ongoing academic supervision and conceptual guidance. 3.Writing: Reviewed and edited on manuscript draft.
Paper B Conference paper	1. Conceptualisation: Defined the research aim and developed the coding framework. 2. Methodology: Designed the qualitative approach and conceptual framework. 3. Data collection: Extracted relevant content from the Swedish national curriculum. 4. Data curation: Organised text for NVivo-based analysis. 5. Formal analysis: Conducted coding and synthesised results. 6. Investigation: Reviewed literature to support analytical design and results. 7. Visualisation: Developed tables to represent results. 8. Writing: Drafted the full manuscript. 9. Correspondence: Served as corresponding author; coordinated submission process and implemented reviewer feedback.	1.Validation: Supported the verification of coding strategies and interpretation of data. 2. Supervision: Provided academic supervision and conceptual guidance throughout the research process. 3. Methodology: Contributed to refining the qualitative research design and coding framework. 4. Data curation: Supported the organisation and preparation of data for analysis. 5. Formal analysis: Participated in the coding process through collaborative discussions, codebook refinement, and validation of emerging themes. 6.Writing: Reviewed and edited on manuscript draft.

Papers	Author of the thesis	Supervisors
Paper C Peer-reviewed journal article	1. Conceptualisation: Refined the research aim and extended the coding framework. 2. Methodology: Designed the qualitative approach and conceptual framework. 3. Data collection: Extracted content from the updated Swedish national curriculum. 4. Data curation: Organised text for NVivo-based analysis. 5. Formal analysis: Conducted coding and synthesised results. 6. Investigation: Reviewed literature to support analytical design and results. 7. Visualisation: Created visual matrices and summary tables. 8. Writing: Drafted the manuscript and contributed to the overall review and refinement of the manuscript. 9. Correspondence: Served as corresponding author; coordinated submission process and implemented reviewer feedback.	1.Validation: Supported the verification of coding strategies and interpretation of data. 2. Supervision: Provided academic supervision and conceptual guidance throughout the research process. 3. Methodology: Contributed to refining the qualitative research design and coding framework. 4. Data curation: Supported the organisation and preparation of data for analysis. 5. Formal analysis: Participated in the coding process through collaborative discussions, codebook refinement, and validation of emerging themes. 6.Writing: Contributed to the original manuscript and participated in reviewing and editing the draft.
Paper D Peer-reviewed journal article	1. Conceptualisation: Developed the research question and expanded the coding framework. 2. Methodology: Designed the qualitative approach and conceptual framework. 3. Data collection: Extracted content from all subject syllabi in the Swedish curriculum. 4. Data curation: Organised text for NVivo-based analysis. 5. Formal analysis: Conducted coding and synthesised results. 6. Investigation: Reviewed literature to support analytical design and results. 7. Visualisation: Designed tables and visual summaries. 8. Writing: Drafted the full manuscript. 9. Correspondence: Served as corresponding author; coordinated submission process and implemented reviewer feedback.	1.Validation: Supported the verification of coding strategies and interpretation of data. 2. Supervision: Provided academic supervision and conceptual guidance throughout the research process. 3. Methodology: Contributed to refining the qualitative research design and coding framework. 4. Data curation: Supported the organisation and preparation of data for analysis. 5. Formal analysis: Participated in the coding process through collaborative discussions, codebook refinement, and validation of emerging themes. 6. Writing: Reviewed and edited on manuscript draft.

Papers	Author of the thesis	Supervisors
Paper E [Under review of a Peer-reviewed journal article]	1. Conceptualisation: Defined comparative research aim and selected analytical frameworks. 2. Methodology: Designed the phenomenological approach and interview protocol. 3. Data collection: Conducted online interviews with teachers from Sweden and Ireland. 4. Data curation: Transcribed and organised qualitative data. 5. Formal analysis: Performed analysis of interview transcripts. 6. Investigation: Reviewed relevant literature to support analytical design and results. 7. Visualisation: Designed tables and visual summaries. 8. Writing: Drafted the full manuscript. 9. Correspondence: Served as corresponding author; coordinated submission process and will implement reviewer feedback.	1. Validation: Supported the verification of interview strategies and interpretation of findings. 2. Supervision: Provided academic supervision and conceptual guidance throughout the research process. 3. Methodology: Contributed to refining the interview protocol and methodological design. 4. Formal analysis: Participated in the interview analysis process through collaborative discussions and validation of emerging themes. 5. Writing: Reviewed and edited on manuscript draft.

1.5.3. Publication Strategy

The dissemination strategy for the five papers included in this thesis was shaped by the relevance of the journal or conference to the research topic, target readership within the education and STEM research communities, and the opportunities for timely and open dissemination. Each venue was selected in consultation with supervisors and based on the scope, visibility, and academic standards of the outlet.

Paper A: Frontiers in Education.

The journal was selected for its strong alignment with curriculum reform, spatial ability, and STEM education. The journal's open-access model and its dedicated section on STEM and curriculum studies made it well-suited to reach interdisciplinary educational audiences. At the time of submission, the journal was indexed in major academic databases (e.g., Scopus) and remained active within scholarly conversations on STEM curriculum and teacher education. This paper also served as an early deliverable for the EU-funded SellSTEM project, and its publication supported the project's goal of reaching a broad readership, including policy actors, curriculum developers, and researchers, to raise awareness of spatial ability in education. The journal's accessibility and disciplinary scope supported this broader outreach objective.

Paper B: PATT40 Conference Proceedings (PATT40).

The conference was chosen due to its established reputation in Technology education research and its focus on curriculum and Design education. This conference paper explored spatial ability within the Swedish Craft and Technology curriculum, a topic directly aligned with the PATT community. Presenting at PATT40 enabled direct engagement with scholars and practitioners focused on Technology education. Feedback received during peer review and conference discussions informed the methodological and conceptual developments in Paper C, which extends this line of research.

Paper C: International Journal of Technology and Design Education (IJTDE).

Building on insights from Paper B, this paper was submitted to IJTDE, a peer-reviewed journal known for its focus on Technology education and curriculum design, which are both central to Paper C. The paper refined the analytical framework introduced in Paper B and applied it to the updated Swedish curriculum. Reviewer feedback from both the conference and journal stages helped shape the study's methodological rigour. The journal was chosen to

continue engaging audiences focused on technology-specific pedagogy and curriculum research.

Paper D: Heliyon.

The journal was selected for its interdisciplinary scope and open-access format, which supports the broad dissemination of research to both academic and professional audiences. This paper presents a whole-curriculum analysis of all subjects in the Swedish compulsory school system. It positions spatial ability as a concept that extends beyond STEM and is relevant across multiple subject areas. The aim was to engage not only education researchers but also scholars within individual disciplines such as Science, Mathematics, Languages, and the Arts. Publishing in a journal with a broad disciplinary readership was a deliberate choice to support dialogue that reaches beyond educational research and into subject-specific domains.

Paper E: Teaching and Teacher Education.

This manuscript, currently under review, explores Mathematics teachers' experiences in developing students' spatial ability in Ireland and Sweden. The journal was selected because of its strong focus on teaching practice and teacher education, which aligns with the study's emphasis on curriculum enactment and teacher agency. In addition, the journal has featured several studies set in Nordic and Irish contexts, indicating an existing readership likely to engage with research situated in these regions. However, spatial ability remains relatively underexplored within this body of work. By addressing it through a comparative lens, this paper aims to add a new perspective to ongoing conversations in this community and contribute to a broader understanding of how teachers navigate and implement curriculum priorities across national contexts.

2. Background and Foundations

Researchers adopt paradigms that reflect their assumptions about reality, knowledge, and meaning (Deetz, 2001). However, in spatial ability literature, researchers' paradigms are often implicit, requiring readers to infer their theoretical perspectives, values, and interpretative meanings. This lack of clarity can obscure how theories are applied and evaluated in specific contexts.

This chapter addresses that gap by tracing the evolution of spatial ability research, positioning it within broader ontological and epistemological shifts. It first explores the historical roots of spatial ability as a psychological construct, highlighting early conceptualisations and their connections to psychometrics and cognitive science. It then examines how large-scale quantitative studies, particularly those linking spatial ability to academic achievement, have shaped dominant understandings within the field. Finally, the chapter discusses emerging movements toward interpretivist perspectives, focusing on how recent research engages teachers' beliefs, perceptions, and classroom practices.

2.1. The Root of Spatial Ability Literature

The concept of spatial ability was first introduced by Sir Francis Galton in 1879, who referred to it as a "visualising faculty." Galton, a British scientist and cousin of Charles Darwin, was heavily influenced by Darwin's theory of evolution by natural selection. Galton's interests spanned Genetics, Heredity, Psychology, Statistics, Anthropometry, Geography, and Meteorology, marking him a polymath.

In 1879, he defined "visualising" as the "powers of seeing well-defined images in the mind's eye" (Galton, 1879, p.158). In his work *Generic Images* (1879), Galton observed that our memories are not always precise but rather a blended combination of features we have seen before, similar to how artists capture the essence of a group rather than an exact individual likeness. According to Galton, diverse images might occur in our minds when we recall an image and generate some generic or "average" features. Galton adopted a composite photography technique to represent how our minds form the generic image. Specifically, he overlaid photographs of multiple persons. Then, he looked for the average features of these persons. He repeated the technique within various groups to identify the common features among the persons within each group, such as family members, criminals, and groups of certain occupations. This work laid the groundwork for psychometrics and statistics. Figure 2 shows an example of his work on identifying common features of criminals.

Figure 2:Example of Galton's (1879) work.[6]

Galton's (1879) conception of the "visualising faculty" also reflected a multidimensional understanding of mental imagery. He observed that individuals varied not only in their ability to visualise clearly, but also in the complexity, vividness, and manipulation of images they could produce

[6] Composite photograph by Francis Galton, originally published in 1879 by William Clowes and Sons. Reprinted from Proceedings of the Royal Institution (Vol. 9, pp. 161–170) with minor variations. Image retrieved from galton.org (public domain).

mentally. This recognition of qualitative differences across visualisation processes paved the way for later conceptualisations of spatial ability as a multifaceted construct, incorporating diverse cognitive skills such as mental rotation, orientation, and transformation — elements that remain central to contemporary models of spatial ability today.

In Galton's work, terms such as "truth", "test", "statistics", "powers", and "accuracy" were frequently used, might reflect his commitment to an ontology of realism and an epistemology of positivism in his journey of scientific research—a research paradigm that assumes an objective reality exists independently of human perception. It emphasises empirical observation, measurement, and scientific methods to uncover universal truths. Across the disciplines of Genetics and Heredity, Psychology, Statistics, Anthropometry, Geography, and Meteorology, he consistently devoted himself to discovering the "truth", revealing the universal laws that could improve human well-being, and emphasising the robust research approach that could yield strong validity and reliability. Given that contemporary spatial ability literature can be traced back to Galton's foundational work, it is likely that his ontological and epistemological orientations have influenced spatial ability researchers for generations.

Ontology concerns the nature of reality, addressing fundamental questions such as: is reality independent or mind-constructed? (Greenfield & Ribbins, 2005; Hitchcock & Hughes, 1995; Pring, 2015). Ontology shapes epistemology, which focuses on how knowledge is acquired and understood (Hitchcock & Hughes, 1995). It determines whether knowledge is objective, observable, and measurable, or subjective, personal, and embedded in human interaction. Ontology and epistemology underpin research design, dividing it into objectivist and subjectivist approaches. They further influence methodological choices, which, in turn, determine instrumentation, data collection, and analysis. Examining the ontological and epistemological foundations of spatial ability literature provides insight into how researchers conceptualise spatial ability, its significance, and the most valid approaches to its development.

Before proceeding with the literature review, Table 2 outlines the definitions of key ontology and epistemology referenced in this study.

Table 2:Key ontology and epistemology (Cohen et al., 2018; Djamba & Neuman, 2002; Greenfield & Ribbins, 2005; Hitchcock & Hughes, 1995; Pring, 2015).

Ontology	Definition	Epistemology	Definition	Approach
Idealism	Idealists believe reality is shaped by human interpretation, seeing the universe as meaningful only when people construct and assign meaning to their thoughts and experiences.	Interpretivism	Interpretivists value individuals' subjective experiences and the meanings they assign to phenomena. They emphasize that the complexity of human interaction and behaviour requires nuanced interpretation, considering each case within its unique context.	Subjectivist
Realism	Realists argue that an objective world and truth exist independently of human interpretation and perception. They believe reality is fixed and can be understood through systematic observation, analysis, and inquiry.	Positivism	Positivists argue that knowledge is derived solely from empirical, measurable evidence and is meaningful only when logically verified. They prioritize facts, direct observation, and statistical data over subjective experience.	Objectivist

Spearman (1904) and Thurstone (1938) were two other important figures in the development of spatial ability literature. Influenced by Galton's work, Spearman introduced the use of factor analysis in the study of human intelligence, a method that has been impacting the subsequent conceptualisation of spatial ability. Spearman proposed that human intelligence comprises a second-order model with general intelligence (g) and specific abilities (s). General intelligence (g) is involved in all mental tasks, while specific abilities (s) pertain to intellectual capacities in specific areas. Echoing Galton's work, perhaps we can understand g as the generic image within a particular group, while s could be understood as the individual variations of each group member.

As an alternative to Spearman's model, Thurstone (1938) developed a multi-factor model of intelligence that excluded the general factor (g) proposed by Spearman. Thurstone argued that human intelligence should be understood as

comprising seven independent primary mental abilities rather than a single quotient. In this model, "space" was identified as one of these primary mental abilities, corresponding to what we now refer to as spatial ability.

Building on the foundational work of Spearman (1904) and Thurstone (1938), subsequent researchers have continued to explore the relationship between spatial ability and human intelligence. Vernon (1950), for example, expanded on Spearman's model, positing that general intelligence (g) is the primary factor from which spatial ability is derived. Guilford (1967) further extended Thurstone's work by identifying mental content dimension—representing spatial ability—an independent ability that forms human intelligence.

During the conceptualisation journey, Meehl (2006) noted that the definitions of spatial ability were verbally established without sufficient empirical evidence. As the debate evolved, various descriptions of spatial ability emerged. Chronologically, Lohman (1979, p.126) conceptualised spatial ability as "the ability to generate, retain, and manipulate abstract visual images". Sorby (1999, p.21) described it as the "innate ability to visualise that a person has before any formal training has occurred". Gaughran (2002, p.3) described it as "the ability to visualise, manipulate and interrelate real or imaginary configurations in space". These conceptualisations emphasise various cognitive processes involved in spatial ability, yet they differ in scope and emphasis.

In response to this conceptual variation, more formalised theoretical frameworks have emerged. One of the most widely accepted today is the Cattell-Horn-Carroll (CHC) theory (Schneider & McGrew, 2018). This theory integrates two foundations. The first is the Gf-Gc model developed by Cattell and Horn (Cattell, 1943; Cattell & Horn, 1978; Horn, 1985; Horn & Cattell, 1966). Fluid intelligence (Gf) refers to the capacity to reason and solve unfamiliar problems, such as mentally rotating objects or identifying novel patterns, without relying on prior learning. In contrast, crystallised intelligence (Gc) refers to knowledge and skills acquired through education and experience, such as vocabulary or factual information. Spatial ability is typically classified under fluid intelligence, as it requires flexible problem-solving based on mental imagery rather than accumulated knowledge. The second foundation of CHC thoery is Carroll's (1993) three-stratum theory, which organises cognitive abilities in a hierarchical structure. At the base are narrow, task-specific abilities; the middle stratum includes broader domains such as visual-spatial reasoning and verbal comprehension; and at the top is general intelligence (g), which influences performance across all levels. By synthesising these two

frameworks, the CHC theory offers a comprehensive model of human intelligence in which spatial ability is positioned as a second-order ability, nested within a broader system of interrelated cognitive processes.

The CHC framework also incorporates elements of both Spearman's and Thurstone's work on intelligence. It retains Spearman's (1904) concept of g as a third-order factor that exerts overarching influence on all cognitive domains. At the same time, it acknowledges Thurstone's (1938) emphasis on distinct cognitive factors by recognising multiple first-order abilities. In this structure, spatial ability is not treated as a standalone trait but rather as one of 16 second-order abilities with 11 discrete constituting spatial factors. This positioning reflects the complexity and interdependence of cognitive skills involved in spatial reasoning and underscores the importance of considering spatial ability within a broader, empirically validated model of intelligence.

For decades, most spatial ability literature has shared and is still sharing Galton's positivism, endeavouring to reveal the universal laws that could improve spatial ability in human intelligence, especially in the disciplines of education. To date, spatial ability literature has covered various topics, such as the conceptualisation of spatial ability (e.g., Buckley, et al., 2018), educational intervention (e.g., Uttal, et al., 2013), cognitive and neuroscientific development (e.g., Newcombe, 2020), and gender differences (Bartlett & Camba, 2023), etc. Thus, the conceptualisation of today's spatial ability has evolved from Galton's (1879) initial depiction of "visualising" to encompass a broader and more complex set of dimensions.

2.2. The Development of Spatial Ability Literature: Spatial Ability and Academic Achievement

While technological advancements have significantly transformed the world, there are pressing challenges today that education must address to ensure a better future. According to Bloom et al.'s taxonomy, learning should encompass the cognitive, affective, and psychomotor domains (Bloom et al., 1964). In the cognitive domain, the goal of education is to equip students with specific disciplinary knowledge in more than one field (Gao et al., 2021; Kurup et al., 2021). For example, a common approach in STEM education is the use of engineering design to enhance problem-solving skills in Mathematics and Science, where one discipline (i.e., Engineering) serves as a tool for learning other subjects (i.e., Mathematics and Science). This method aligns with the growing emphasis on interdisciplinary education. By fostering cognitive

capacity that spans across multiple subjects, interdisciplinary education, such as STEM education, empowers students to make informed decisions[7]. This capacity is built through shared learning experiences that can be applied across disciplines. With this cognitive capacity foundation, students develop a sense of ownership over their knowledge, enabling them to retain and apply it throughout their lives (Kurup et al., 2021).

Recent research highlights spatial ability as such a critical cognitive capacity relevant across nearly all subjects, contributing significantly to academic success (Buckley et al., 2022; Lane et al., 2019; Zhu et al., 2023; Lin et al., 2024a). Spatial ability, recognised as a core component of human intelligence, allows individuals to "…perceive complex patterns and mentally simulate how they might look when transformed (e.g., rotated, twisted, inverted, changed in size, partially obscured)" (Schneider & McGrew, 2018, p. 126). Evidence suggests that limited spatial ability may hinder students from fully engaging with educational content, especially in many STEM subjects where spatial reasoning is inherently demanding. For example, spatial ability is integral to Mathematics (Mix et al., 2021), Geology (Hambrick et al., 2012), Physics (Kozhevnikov et al., 2007), and Engineering (Sorby, 2024). In Mathematics, spatial ability plays a role in Geometry and Boolean operations, while subjects like Chemistry, Biology, and Technology involve spatial reasoning when understanding object structures—such as particle models, organ locations, or computer components (Lin et al., 2024a).

Spatial ability has been explored and suggested to comprise a great variety of factors and dimensions. To date back, McGee (1979) suggested that spatial ability includes the dimensions of spatial visualisation and spatial orientation. While spatial visualisation manipulates objects in the mind, spatial orientation perceives objects from various perspectives. Lohman (1988) added a dimension of speeded rotation, which refers to the ability to identify the rotated version of a two-dimensional object quickly. Later, Carroll (1993) further concluded that spatial ability should include five main dimensions: visualisation, spatial relations, closure speed, closure flexibility, and perceptual speed. Today, the potential factors and dimensions of spatial ability are still being expanded and revealed. Some examples of the exploration could be

[7] **Informed decision:** A decision based on relevant, accurate, and well-evaluated information, considering evidence, expertise, and contextual factors to achieve a rational and well-justified outcome.

Newcombe and Shipley's (2014) typology that based spatial ability on the dimensions of intrinsic-extrinsic and static-dynamic, Buckley et al.'s (2018) heuristic framework that uncovered 25 spatial factors that could be translated into educational practice in STEM learning, and Posamentier et al.'s (2021) spatial model that offered 8 elements for educators to "diagnose, train, and foster one's visual perception and spatial abilities" (p.25). It seems that current spatial ability researchers are following in the footsteps of pioneers like Galton (1879), Spearman (1904), and Thurstone (1938). They metaphorically overlay "photographs" of diverse spatial ability performances to identify average patterns among these performances, thereby aiming to understand human variations and inherited traits. This approach continues to build on the foundational work of these early scholars, seeking to reveal underlying principles and patterns in spatial ability.

Stieff and Uttal (2015) reported that the previous evidence for the effectiveness of spatial training on educational achievement was empirically inadequate. The lack of evidence could be due to "flawed studies, imperfect interventions, or the limited applicability of spatial ability for STEM learning is unclear, and the true effect of spatial training interventions remains unknown" (Stieff & Uttal, 2015, p.613). Hence, spatial ability researchers have been responding to the compelling need to strengthen the explanatory power of the causal relationship between academic achievement and spatial ability. Wai et al. (2009) tracked a large number of high school students ($n \approx 400{,}000$) for over 11 years. Their findings revealed that students with high spatial ability were more likely to pursue higher education and careers in STEM fields. Moreover, the study suggested that spatial ability could help identify latent STEM talents, which might be overlooked by conventional talent identification methods (Wai et al., 2009). Sorby et al.'s (2018) findings, obtained from a sample of 3,948 college students over a five-year period, demonstrated that spatial training led to significant improvements in retention rates among female engineering students. Sorby and colleagues attributed this outcome to the enhancement of spatial ability, which likely unlocked students' mathematical potential and played a pivotal role in their Engineering education. In addition, Judd and Klingberg (2021) published a study with a sample of 17,648 young children, investigating the effect of spatial training on mathematical learning. These empirical findings gave researchers statistical confidence in the effectiveness and efficacy of spatial training, which encourages a global effort to promote academic achievement by employing spatial training. The above indicates that

the positivist perspectives have been taken here as spatial ability researchers are consistently looking for the "evidence" and "truth".

2.3. The Shift of Ontology and Epistemology in Spatial Ability Literature

In recent years, spatial ability researchers have not only emphasised what should be developed in students' spatial ability but also how to effectively develop spatial ability. Studies focusing on teachers' perceptions, beliefs, attitudes, awareness, and understanding of spatial ability have emerged to cultivate students' spatial ability more effectively. For example, Gagnier et al. (2022) investigated elementary teachers' beliefs, perceptions and self-efficacy for developing spatial ability for students, and Burte et al. (2020) analysed how elementary Mathematics teachers' attitude and beliefs affected their Mathematics and spatial ability instruction for students. Most of these studies also took a positivist perspective. They explored how teachers "feel", "believe", and "understand" the role of spatial ability through statistical evidence obtained from a measurable Likert scale. While the ultimate research goal of these studies is to touch on teachers' value systems and reveal how they make sense of education, there seems to be scarce discussion on how teachers make meanings out of their experience—the interpretivist perspective.

Interpretivism is grounded in an ontology that contrasts with the traditional spatial ability literature. As discussed in the last paragraphs, spatial ability literature is predominantly grounded in positivism following an objectivist approach, whereas interpretivism is rooted in a subjectivist approach (Schutz, 1967). In recent years, only a few articles seemed to take interpretivism when uncovering spatial ability development for students.

One of the first was Ramey and Uttal's (2017) study of how middle school students developed spatial ability during a summer Engineering camp. Through classroom observations, they showed that students made sense of spatial-related problems by combining their own thinking with collaboration and hands-on interaction with materials, highlighting that spatial ability developed through social and contextual experiences. Next, Gumaelius et al. (2018) studied Korean and Swedish teachers' views on training spatial ability for students. The study explored how teachers of the two countries defined spatial ability, how they perceived the role of national policy documents in developing spatial ability, and what they perceived as preconditions and limitations of developing spatial ability in classrooms. Power and Sorby (2021) studied middle school teachers' perceptions of the effectiveness of spatial

training. Their study focused on how teachers' perceptions of effectiveness affected their implementation fidelity—the degree to which a program, intervention, or instructional approach is delivered as intended by its original design (O'Donnell, 2008). Nguyen et al. (2024) studied Geography teachers' perceptions of spatial ability regarding how much they understood spatial ability, how they taught it, and what they had seen as the factors that influenced their teaching. These studies employed qualitative approaches to emphasise individual experiences and interpret how teachers and students make sense of their decisions and enacted practices. However, they did not thoroughly discuss the theoretical foundations guiding their investigations and interpretation.

Gagnier et al.'s (2022) study may be the most relevant resource for exploring the theoretical background of teacher perceptions. Although Gagnier et al. (2022) employed a quantitative approach, they drew on Bandura's social cognitive framework (1986), which integrates both objectivist and subjectivist approaches. Bandura (1986) recognised that an objective reality exists, separating from individual perceptions. He also emphasised that this reality further influences behaviour. In addition, he emphasised the crucial role of cognitive processes, such as beliefs, in shaping behaviour and interacting with the objective world. This approach reflects a dualist perspective, where researchers integrate empirical observation with individual meaning-making, acknowledging that knowledge arises from both external facts and personal experiences (Andreea & Hélène, 2023; Mensch, 2023; Overgaard, 2023).

2.4. A Way of Moving Forward—The Interpretivism Paradigm

While subjectivist approaches remain less common in spatial ability research, they offer valuable complementary perspectives to the traditionally dominant positivist approaches. Growing interest in subjectivist inquiry reflects a broader shift toward a more holistic and multifaceted understanding of how spatial ability develops in educational settings. By incorporating subjectivist perspectives, research can provide richer, context-specific insights that deepen and extend existing knowledge. Building on this view, this thesis adopts an interpretivist paradigm with a subjectivist approach, aiming to move beyond traditional boundaries and contribute to a more nuanced understanding of spatial ability development.

3. Methodology

3.1. Methodological Foundations: Paradigm and Theoretical Orientation

This thesis examines both curriculum structure and teachers' lived experience, both of which are shaped by individual experiences. While a country's curriculum is established according to specific educational traditions and is influenced mainly by national perspectives, teachers' lived experience reflects their personal insights. Both perspectives are central to developing spatial ability for students, as they inform and guide the teaching-learning processes that shape student outcomes.

To capture these dimensions, this thesis integrates both quantitative and qualitative methods within the interpretivism paradigm. An interpretivism paradigm posits that reality is socially constructed through individual experiences and social interactions, shaped by specific contexts (Willis, 2007). This paradigm has gained increasing influence in the 21st century. Rather than seeking to explain or generalise universal laws, interpretivism research prioritises understanding the world from the perspectives of those who inhabit it. While interpretivist researchers may employ quantitative methods similar to those used by positivism researchers, their approach to interpretation fundamentally differs. Rather than seeking objective generalisations, they focus on the subjective meanings, lived experiences, and contextual influences underlying the data (Willis, 2007).

One key methodological approach that aligns with interpretivism is grounded theory. It was introduced by Glaser and Strauss in 1967 through their seminal work, *The Discovery of Grounded Theory: Strategies for Qualitative Research*. Glaser and Strauss (1967, p. 1) described it as the "discovery of

theory from data." They advocated for qualitative research as a means to develop theories, arguing that research should go beyond passively accepting existing theories or merely testing them through quantitative methods.

Grounded theory serves as a methodology that systematically generates theory from social research data. Its primary outcome is a theory or conceptual framework to guide further inquiry. This concept emerged during the paradigm shift of the modernist era (1950–1970), a time of transition from positivism to post-positivism (Charmaz, 2014; Denzin & Lincoln, 2018). Unlike positivism, post-positivism recognises that researchers' values and biases influence research findings. It argues that truth can only be approximated through interactions with research participants (Creswell & Poth, 2018).

However, after publishing their work, Glaser and Strauss took divergent paths. Glaser's later work leaned toward positivism, emphasising maximum objectivity in research (Rieger, 2019; Singh & Estefan, 2018). In contrast, Strauss, in collaboration with Corbin, adapted grounded theory to align more with interpretivism. He argued that strict objectivity is unattainable, and that theory is co-constructed through interactions between researchers and participants (Strauss & Corbin, 2015).

Other than grounded theory, the phenomenological approach is also widely adopted within the interpretivist paradigm. While often mistaken for phenomenology as a philosophy, it is a distinct research methodology (Urcia, 2021). Husserl first promoted this approach to explore and understand individuals' lived experiences, aiming to uncover the essence of consciousness. Like grounded theory, the phenomenological approach emerged during a time when positivism dominated research. Husserl, aligned initially with positivism, later embraced post-positivism after recognising lived experiences as an essential source of knowledge (Husserl, 2012). However, similar to Glaser's grounded theory, Husserl initially advocated for minimal researcher interpretation when describing lived experiences.

This perspective evolved with Heidegger's contributions, as he adapted the phenomenological approach to incorporate meaning interpretation (Heidegger, 1962). Similarly, just as Strauss and Corbin (2015) emphasised interpretation in grounded theory, Heidegger encouraged researchers to explore the underlying meanings of a phenomenon rather than merely bracketing their preconceptions.

In this thesis, both Strauss and Corbin's (2015) grounded theory and Heidegger's (1962) phenomenological approach are embraced. Their shared emphasis on interpretation and meaning making provides the necessary flexibility to explore the dynamic and complex development of spatial ability within educational contexts. Although the terms grounded theory and phenomenological approach are not explicitly referenced in the appended papers, they underpin the research methods and inquiries, guiding the investigation of the central research question: How is the development of spatial ability situated within the national curriculum and supported through educational practice?

3.1.1. Approach I: Grounded Theory

Grounded theory is adopted to address the first sub-research question: How is spatial ability represented and structured within the national curriculum?

Grounded theory is ideal as it emphasises inductive reasoning. It aligns with the intention to understand the national curriculum from the document itself rather than imposing predefined frameworks. Papers A, B, C, and D follow grounded theory. In addition, Papers C and D specifically contribute to developing a new conceptual framework, which guides further inquiry. Document analysis serves as the primary data source in these papers.

3.1.2. Approach II: Phenomenological Approach

The phenomenological approach is adopted to address the second sub-research question: How do teachers perceive and implement the role of spatial ability within the national curriculum?

Paper E employs a phenomenological approach, using interviews to explore how teachers interpret spatial ability development within curriculum guidelines. The paper aims to uncover their lived experiences in daily teaching, providing deeper insights into their perspectives and practices.

3.2. Research Design and Methodological Rationale

In Paper A, narrative analysis with thematic categorisation was considered the most suitable approach for synthesising curriculum documents from the four selected countries. This method offered a way to construct a comparative perspective by linking curriculum structures to broader educational priorities. As the analytical interest lay in identifying structural patterns and thematic

orientations at a systems level, rather than analysing texts line by line, coding was not applied.

For Papers B to D, document analysis was selected after reviewing alternative approaches for examining how spatial ability is represented in the curriculum documents. It allowed for systematic comparison while supporting a bottom-up perspective of interpreting curricula through the lens of teachers and curriculum developers, rather than imposing an external research framework. Coding was adopted to identify both explicit and implicit spatial-related references. NVivo was used to organise and document the coding process, supporting transparency and dependability (Shenton, 2004).

In Paper E, interviews were chosen following a review of relevant methods. Surveys were considered but found inadequate for capturing the depth of teachers' reasoning and contextual interpretation. Interviews provided the flexibility to explore how teachers connect ideas, values, and practices in relation to spatial ability. They are also effective for uncovering how individuals construct meaning, which surveys often fail to reveal (Cohen, et al., 2018). The interview data were analysed using Moustakas' (1994) phenomenological steps, which prioritise the interpretation of lived experience. This aligned with the study's aim to understand how teachers engage with curriculum intentions in practice.

Each method was selected through a process of methodological reasoning, weighing alternatives and aligning with the research aims. Table 3 summarises the research design of the appended papers.

Table 3: Research design of the appended papers.

Paper	Guiding methodological approach	Research question(s)/aim(s)	Research method	Data and data collection	Data analysis
Paper A: Addressing the complexity of spatial teaching.	Grounded theory	What are the enablers and barriers when implementing spatial activities in primary-level Science and Mathematics across different countries?	Narrative review	Primary-level curricula for Mathematics and Science in Ireland, the Netherlands, Latvia, and Sweden; A selection of relevant literature.	Narrative analysis with thematic categorisation.
Paper B: Situating spatial ability in Craft and Technology.	Grounded theory	To examine the locations of spatial ability within the Craft and Technology curricula in Swedish compulsory education.	Document Analysis	Craft and Technology syllabi in the Swedish National Curriculum (revised in 2018).	Content analysis with coding by using the software Nvivo 12.
Paper C: The potential for spatial ability development through the Swedish Technology and Craft curricula.	Grounded theory	Where is potential spatial ability development located in the Swedish compulsory Technology and Craft curricula, either explicitly or implicitly?	Document Analysis	Technology and Craft syllabi in the Swedish National Curriculum (2024).	Content analysis with coding by using the software Nvivo 12.
Paper D: Locating the potential development of spatial ability in the Swedish national curriculum.	Grounded theory	How can spatial ability be potentially identified and interpreted in the Swedish national curriculum?	Document Analysis	Chapter 5 Syllabuses in the Swedish National Curriculum (2024).	Content analysis with coding by using the software Nvivo 12.

Paper	Guiding methodological approach	Research question(s)/aim(s)	Research method	Data and data collection	Data analysis
Paper E: (Manuscript): How do teachers experience developing students' spatial ability?	Phenomenological approach	How do Irish and Swedish Mathematics teachers experience spatial ability development in the national curriculum?	Phenomenological approach	Interviews with six Mathematics teachers.	Moustakas' (1994) phenomenological analysis steps.

3.3. Trustworthiness

Since the appended papers are qualitative, they establish trustworthiness using Shenton's (2004) framework, addressing credibility, transferability, dependability, and confirmability.

Credibility, which ensures the accuracy of findings, is supported through methodological rigour and validation strategies. Paper A (Bufasi et al., 2024) enhances credibility through the systematic selection of research sources, cross-examining international literature and curricula from Ireland, Latvia, Sweden, and the Netherlands. Papers B, C, and D (Lin et al., 2023, 2024a, 2024b) apply NVivo-supported qualitative content analyses, using in-vivo, descriptive, and axial coding to systematically identify curriculum components related to spatial ability. Paper D further supports credibility by incorporating quantitative frequency analysis, allowing measurable validation of qualitative findings. Paper E (manuscript), a phenomenological study, employed member checking, where teachers reviewed interview summaries to ensure an accurate representation of their experiences. Moreover, across all papers, the research team possesses expertise in curriculum studies and spatial ability education in both Swedish and Irish contexts. The researchers' background in STEM education, teacher training, and educational policy analysis enhances the credibility of interpretations. Additionally, in Paper E, cross-national collaboration ensures a balanced perspective, preventing bias from national curriculum familiarity.

Transferability relates to the applicability of findings to different contexts. It is reinforced through detailed descriptions of research settings and data sources, allowing results to be applied to other settings when relevant. Paper A examines multiple European curricula, offering broad applicability. Papers B, C, and D provide in-depth documentation of the Swedish National Curriculum, explicitly analysing Chapter 5 "Syllabuses", which guides subject-specific learning objectives. Paper E strengthens transferability through cross-country comparisons, contrasting teachers' autonomy in Sweden with policy-driven curriculum implementation in Ireland.

Dependability, the consistency and replicability of findings, is strengthened through intercoder reliability and systematic documentation. Papers B, C, and D apply NVivo-based coding, with multiple researchers independently coding curriculum documents before reconciling discrepancies. Paper E employs researcher triangulation, where multiple researchers coded interviews

separately before discussing and refining interpretations. All methodological steps were documented to allow future replication.

Confirmability, ensuring that findings are derived from the data rather than researcher bias, is explicitly supported by reflexivity, particularly in Paper E. Reflexivity is achieved through bracketing (epoché), where researchers set aside prior assumptions about spatial ability instruction. Reflexive journaling further ensures ongoing self-awareness of potential biases. Additionally, Paper E applies imaginative variation, a technique in phenomenological studies where researchers critically explore alternative interpretations of interview data to prevent bias from influencing conclusions. Papers B, C, and D reinforce confirmability by employing NVivo-supported coding, allowing multiple researchers to cross-validate how curriculum elements were categorised. Paper D further reduces subjectivity by introducing quantitative frequency analysis, objectively measuring the occurrence of spatial ability references within the curriculum. Table 4 outlines how trustworthiness was established across the appended papers in this thesis.

Table 4:Trustworthiness criteria based on Shenton's (2004) framework.

Criteria	Implementation across papers
Credibility: Establishing accuracy and trustworthiness through rigorous validation.	• Paper A: Systematic source selection; cross-examination of European curricula. • Papers B, C, D: Software (NVivo 12)-supported content analysis (in-vivo, descriptive, axial coding). • Paper D: Quantitative frequency analysis for validation. • Paper E: Member checking with participants; Research team expertise in curriculum studies, STEM education, and policy; Cross-national collaboration to prevent bias.
Transferability: Ensuring applicability to other contexts via detailed contextualization.	• Paper A: Multiple European curricula examined. • Papers B, C, D: In-depth analysis of Swedish National Curriculum, Chapter 5. • Paper E: Cross-country comparison (Swedish teacher vs. Irish teachers).
Dependability: Ensuring consistency and replicability through systematic documentation.	• Papers B, C, D: Inter-raters reliability via software (NVivo 12), independent coding reconciliation. • Paper E: Multiple coders and data sources refining interpretations; Systematic documentation for replication.
Confirmability: Ensuring findings are data-driven, minimizing researcher bias.	• Papers B, C, D: Software (NVivo 12)-supported cross-validation. • Paper D: Quantitative frequency analysis for objective measurement. • Paper E: Reflexivity through bracketing (epoché) and reflexive journaling; Imaginative variation to explore alternative interpretations.

3.4. Ethical Consideration

Ethical considerations guided all stages of this thesis. The research topic was selected based on its critical role in promoting equitable learning opportunities and cognitive development for all students (European Commission, 2024).

In terms of research focus, the appended papers directly and indirectly align with the United Nations Sustainable Development Goals (United Nations, 2015), particularly SDG 4 (Quality Education), SDG 5 (Gender Equality), SDG

8 (Decent Work and Economic Growth), and SDG 10 (Reduced Inequalities). To be specific, by examining how spatial ability can be embedded more systematically within curricula and teaching practices, the papers collectively support equitable access to foundational cognitive skills essential for academic success and lifelong learning. Recognising that gender differences in spatial ability often emerge early and can widen without targeted educational interventions, Papers B–E emphasise the importance of early curriculum integration to promote gender equity and broaden access to STEM pathways. Moreover, by strengthening cognitive foundations necessary for participation in a knowledge-driven economy, the appended papers indirectly contribute to inclusive economic growth and support efforts to reduce inequalities within education systems. These ethical commitments further shaped the selection of methodological decisions and the interpretation of findings throughout the thesis.

In terms of methodology, ethical decisions were made to ensure that all procedures respected the rights, dignity, and well-being of those involved. Papers A–D, based on publicly available curriculum documents and literature, required no formal ethical approval as they did not involve human participants or personal data, ensuring compliance with Swedish research ethics regulations. Nevertheless, academic transparency, critical interpretation, and accurate representation of existing materials were prioritised to maintain research integrity.

For the work described in Paper E, which involved teacher interviews, informed consent was obtained from all participants. Participants were fully briefed on the research purpose, the voluntary nature of participation, and their right to withdraw at any point without consequence. Consent included permission to audio-record interviews and photograph teaching materials, with all data securely stored and accessible only to the research team. Throughout the research process, participant anonymity was preserved, and findings were presented with sensitivity to protect individual and institutional identities.

In terms of interpretation of findings, ethical attention was given to how results were analysed and reported. Efforts were made to avoid misrepresentation, exaggeration, or oversimplification of participants' experiences by ensuring confirmability across the appended papers. The analysis sought to authentically capture the complexities of curriculum and

teaching practices, while recognising the professional expertise and contextual constraints faced by educators.

4. Results and Discussion

This chapter applies Bronfenbrenner's (1976, 1979) ecological systems theory by categorising findings from the appended papers into four interrelated levels: the macrosystem, which shapes spatial ability through policy and curriculum; the exosystem, which influences it through institutional structures and teacher training; the mesosystem, which mediates its implementation through teacher agency and collaboration; and the microsystem, where classroom pedagogy and student engagement determine its direct development. These levels do not function in isolation but interact, meaning changes in one can significantly impact others. This framework enables a critical discussion on systemic barriers, pedagogical strategies, and policy implications for developing spatial ability (Figure 3).

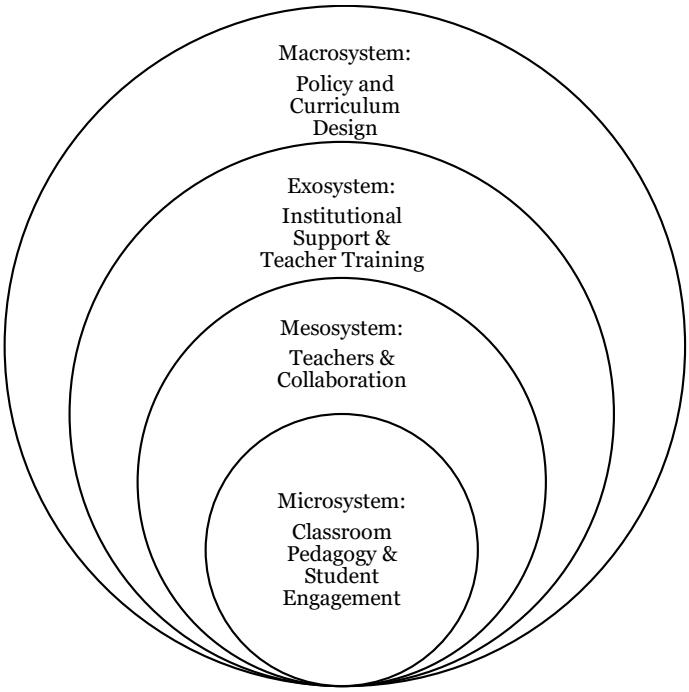

Figure 3:Ecological layers influencing spatial ability development (Adapted from Bronfenbrenner, 1976, 1979).

4.1. Macrosystem: Policy and Curriculum Design

The macrosystem plays a critical role in shaping the development of spatial ability by influencing how national curriculum policies integrate and prioritise it. It determines whether spatial ability is explicitly recognised in policy, how it is embedded within curricula, and the extent to which it is emphasised in educational planning.

Spatial ability research has expanded by identifying a broad range of spatial factors relevant to educational contexts (e.g., Buckley et al., 2018; Newcombe & Shipley, 2014). Much of this work has been grounded in empirical studies that approach spatial ability development from a researcher's perspective using psychometric methods. However, policy contexts remain largely underexamined. One notable exception is Newcombe (2017), who proposed the importance of spatialising the curriculum, though few studies have implemented this idea through the lens of curriculum design.

This thesis addresses that gap by developing a curriculum analysis framework to examine how spatial ability is structured, referenced, or overlooked within national policy documents. Rather than adopting an external research lens, the framework draws on the perspectives of curriculum developers and teachers. In doing so, it shifts the analytical focus to how education systems shape the opportunities for spatial ability development.

In many national curricula, spatial ability is not explicitly recognised as a core learning outcome. Paper A compares curriculum structures across various European countries, revealing notable differences. Ireland, for instance, adopts a structured approach, formally including spatial ability within the Mathematics curriculum under the strand "Shape and Space." In contrast, curricula in Sweden, Latvia, and the Netherlands tend to imply its development within broader strands such as Geometry or assume that it emerges naturally through learning activities in Science subjects.

As argued by Wai et al. (2009) and Schneider and McGrew (2018), spatial ability functions as a potential indicator of cognitive talent. Paper D advances this view by extending the analysis beyond STEM, revealing that spatial ability development potential is also embedded in subjects often overlooked in spatial ability research. A closer examination of the Swedish national curriculum, as presented in Papers B, C, and D, indicates that spatial ability is not formally defined in policy documents. Paper D highlights that in the Swedish National Agency for Education's (Skolverket) national curriculum document, the term "spatial" appears explicitly only in the syllabi for Art, Sign Language for the Hearing, and certain Social Studies subjects, including Geography, History, Religion, and Civics. This may be due to linguistic conventions, as the document was originally translated from Swedish by Skolverket. Nevertheless, this finding contrasts with expectations based on previous spatial ability research, which predominantly associates spatial ability with STEM subjects (Buckley et al., 2022; Gagnier et al., 2022; Hawes & Ansari, 2020).

Papers B and C focus on Technology education through an analysis of the Craft and Technology syllabi in the Swedish national curriculum. Paper B raises concerns about the assumption that spatial ability will develop naturally through related subjects, arguing that without explicit policy mandates, many students do not receive structured opportunities for spatial ability development. Paper C supports this view, demonstrating that while Sweden's Craft and Technology syllabi include activities that enhance spatial ability, many teachers do not explicitly recognise this connection. Without formal

policy guidance, spatial ability often remains secondary to other curriculum priorities. To address this gap, Paper C proposes a conceptual framework to help teachers identify opportunities to develop students' spatial ability through Technology education. Table 5 presents this framework.

Table 5: The 2x3 framework by Paper C.

		Epistemic dimension	
		Conceptual knowledge	**Procedural knowledge**
Visual dimension	**Graphical**	Graphical-Conceptual	Graphical- Procedural
	Property	Property- Conceptual	Property- Procedural
	Manufactured	Manufactured-Conceptual	Manufactured- Procedural

The 2×3 framework presented in Paper C structures spatial ability development across two dimensions: the visual dimension, which defines how spatial information is presented, and the epistemic dimension, which describes how knowledge is acquired. The visual dimension includes three key components: graphical representations (e.g., sketches and schematics), property components (e.g., colour and material characteristics), and manufactured components (e.g., 3D objects and handicrafts). The epistemic dimension consists of conceptual knowledge, which focuses on understanding spatial concepts, and procedural knowledge, which involves learning processes and techniques. This framework enables educators to design lessons that integrate both visual representation and cognitive learning, ensuring a more structured approach to spatial ability development.

The 2×3 framework highlights how spatial ability is embedded in Sweden's Craft and Technology curricula. While Craft activities inherently support spatial ability development, the Technology syllabus offers a broader range of experiences, such as assembly, sketching, and programming. However, teachers may unintentionally downplay the spatial ability aspects of tasks in favour of curriculum-defined knowledge, particularly for students with lower spatial ability.

The study also explores two competing hypotheses regarding spatial ability development. First, the ability-as-enhancer hypothesis, which suggests that students with lower spatial ability may struggle with spatial tasks due to

limited cognitive resources. Second, the ability-as-compensator hypothesis, which proposes that these students benefit more from visual scaffolding, indicating that targeted instructional strategies may help bridge gaps in spatial understanding.

Building on the 2×3 framework, Paper D expands its application beyond Craft and Technology to encompass both STEM and non-STEM subjects. The 3×3 framework extends the epistemic dimension by adding a third component, spatial citizenship, alongside conceptual and procedural knowledge. While the 2×3 framework focuses on how students acquire and apply spatial ability, the 3×3 model incorporates a civic perspective, recognising how learners use spatial information to engage with real-world societal issues. This expansion enhances the original framework by linking spatial ability not only to cognition and hands-on applications but also to students' ability to interpret and communicate spatial information in social and environmental contexts.

A more comprehensive conceptual framework was developed to systematically map spatial ability development across different subjects. This structured approach ensures that spatial ability is not left to chance but is intentionally fostered through targeted educational activities. Table 6 presents the conceptual framework proposed in Paper D.

Table 6:The 3x3 framework by Paper D.

		Visual dimension		
		Graphical	**Pictorial**	**Manufactured**
Epistemic dimension	**Conceptual**	Graphical-conceptual	Pictorial-conceptual	Manufactured-conceptual
	Procedural	Graphical-procedural	Pictorial-procedural	Manufactured-procedural
	Spatial citizenship	Graphical-spatial citizenship	Pictorial-spatial citizenship	Manufactured-spatial citizenship

The definitions of each code in the framework are provided in Appendix B, accompanied by an excerpt from the curriculum to illustrate how specific codes—such as "Graphical-conceptual"—are concretely represented. This example is intended to give stakeholders a sense of how the framework can be applied to their own curriculum contexts. Both Paper B and Paper C highlight that the absence of explicit curriculum policy on spatial ability leads to fragmented and inconsistent implementation across educational systems.

While the 3×3 framework provides a structured approach for integrating spatial ability into syllabi, it lacks policy-driven mandates. As a result, its application depends on individual teacher interpretation rather than standardised curriculum guidelines.

Additionally, Paper D emphasises that in the Swedish national curriculum spatial ability-related content is more prominent in later school years, contradicting research that highlights the importance of early spatial training as a strong predictor of later academic achievement, particularly in Mathematics (Lauer & Lourenco, 2016; Verdine et al., 2017; Zhang et al., 2014). Without curriculum reforms that introduce spatial ability development at an earlier stage, policymakers risk perpetuating academic inequalities and missing a critical window for cognitive development. Addressing this issue requires curriculum policies to (1) prioritise early spatial training as part of foundational education, (2) systematically integrate spatial ability development across subjects rather than confining it to specific disciplines, and (3) establish assessment frameworks that measure spatial ability from early years to ensure long-term academic success.

Although not included among the core publications of this thesis, Malkogeorgou and Lin's (2024) work was developed as a supplementary output to support the application of research insights from Papers B through D. The supplementary article translates theoretical and curriculum-focused themes into concrete recommendations for embedding spatial ability in curriculum design and classroom practice. It proposes actionable strategies that highlight the importance of early spatial ability development, interdisciplinary integration, and consistent implementation across subjects. Key suggestions include clearly stating spatial ability development goals in curriculum documents, using spatial terminology explicitly in subject syllabi (e.g., "spatial awareness" rather than "map use"), and equipping teachers with tangible resources such as spatial tools and exemplar tasks. The following are the key action steps proposed in Malkogeorgou and Lin's (2024) guideline.

- "Step 1: Describe the importance of spatial ability in the goals and objectives of the curriculum. This is to raise teachers' awareness of developing spatial ability through the curriculum.
- Step 2: Use the term 'spatial' in the syllabus where spatial ability is required for certain learning activities. For example, when students are expected to use a map in Geography, rather than simply describing the learning activity as 'using maps', it should be more explicit about the

purpose of 'using maps', which is to increase 'spatial awareness' or 'spatial skills'.

- Step 3: Use the term 'spatial' even more frequently in the curriculum for early stages. This is to raise teachers' awareness of developing young children's spatial ability.
- Step 4: Require spatial tools for teaching materials, such as maps and Lego. This is to make the spatial tasks more explicit and tangible for teachers to apply in classroom.
- Step 5: Attach some exemplars of hands-on spatial tasks as a reference for teachers to apply in classroom, such as the SPACE prompt cards developed by the University of Surrey (2023)."

Moreover, while Paper A demonstrates that Ireland's structured approach provides clearer guidance for teachers, Paper E highlights that despite the benefits of explicit curriculum mandates, rigid assessment structures and curriculum overload make it difficult for teachers to prioritise spatial tasks. Under the Anglo-Saxon curriculum model, Irish teachers are guided by standardised assessment frameworks, meaning spatial ability is more likely to be emphasised if explicitly included in the policy. In contrast, Sweden's didaktik tradition grants teachers greater autonomy, allowing flexibility in implementation but also resulting in inconsistencies. Some teachers actively incorporate spatial ability, while others overlook it.

4.2. Exosystem: Institutional Support and Teacher Training

At the exosystem level, spatial ability development is shaped by institutional structures, particularly the extent to which teacher training programs and professional development prepare educators to integrate spatial ability into their practice. Several studies have examined teachers' attitudes, awareness, and efficacy in supporting spatial ability (e.g., Gagnier et al., 2022; Burte et al., 2020; Power & Sorby, 2021). These studies demonstrate that teacher beliefs and institutional environments significantly influence classroom practice. Many adopt a positivist orientation, using instruments such as Likert-scale surveys to capture generalisable trends. This thesis complements those studies by taking an interpretive approach that explores how beliefs are formed and enacted in institutional settings. This aligns with Gagnier et al.'s (2022) call for a more nuanced understanding of teacher efficacy, and extends it by showing how curricular ambiguity, limited training, and lack of institutional support can restrict spatial ability instruction, even among motivated teachers. The

findings point to the importance of coherent policy guidance, embedded professional learning, and sustained institutional support.

Drawing from Paper A, Ireland's curriculum offers a more explicit orientation toward spatial ability, in contrast to more implicit approaches in Sweden, Latvia, and the Netherlands. Across these contexts, teacher education programs tend to focus on general pedagogy and subject content but rarely position spatial ability as a core competency. To investigate how curriculum structure and institutional support influence practice, Paper E compares teacher experiences in Ireland and Sweden—two countries with contrasting curricular philosophies.

In Ireland, teacher education is relatively structured, and professional development opportunities specific to spatial ability are available. As a result, many teachers report familiarity with the concept through targeted training. However, the structured nature of Ireland's curriculum and assessment system can limit the flexibility teachers have to apply this training in practice. Instruction often remains tied to curriculum-defined objectives, restricting broader integration of spatial thinking. While professional learning exists, pedagogical content knowledge (PCK), the specialised knowledge to transform subject matter into instructional forms that are meaningful and accessible to students, related to spatial ability, develops slowly, in part due to systemic constraints (Gleeson, 2022).

In contrast, Sweden provides teachers with greater curriculum autonomy, but spatial ability is not explicitly embedded in national policy. Consequently, teacher training does not prioritise spatial development, and professional learning in this area is limited. Teachers often draw on personal experience rather than structured preparation (Bladh, 2020; Pettersson et al., 2015). While some participate in broader professional learning, the integration of spatial ability varies widely depending on individual interpretation. This comparison highlights the need for a balance between clear policy support and adaptable teaching practice.

4.3. Mesosystem: Teachers and Collaboration

At the mesosystem level, spatial ability instruction is shaped by teacher agency and collaboration, particularly in how teachers interpret curriculum guidelines and engage with peers to enhance their teaching. Since national policies do not always provide clear directives on spatial ability, teachers need to develop their own approaches to integrating it into their classrooms.

While traditional literature often conceptualised spatial ability within a positivist framework focused on measurement and internal aptitude (e.g., Buckley et al., 2018; Newcombe & Shipley, 2014; Schneider & McGrew, 2018), recent perspectives recognise the importance of contextual and collective meaning-making. In this light, teacher collaboration emerges as a critical site where spatial ability is interpreted, shared, and enacted. The concept of collective PCK reflects this shift, emphasising the role of professional communities in shaping instructional practices (Carlson et al., 2019). This perspective is supported by emerging literature that explores how educators develop understanding of spatial ability through dialogue, peer learning, and contextual negotiation (Gagnier et al., 2022; Gumaelius et al., 2018; Nguyen et al., 2024; Power & Sorby, 2021). By engaging with these dynamics, the mesosystem contributes to a broader understanding of how spatial ability development is mediated through teacher interactions and collaborative cultures.

Paper E examines the role of collective PCK in supporting spatial ability instruction within national curricula. Findings show that in Ireland, teachers primarily access collective PCK through structured professional development and departmental training days, which align instructional practices with national curriculum guidelines. However, since spatial ability is not a mandated priority, teachers' engagement in collaborative lesson planning remains largely dictated by exam structures and procedural learning objectives. Some teachers participate in voluntary conferences and informal peer discussions, but these opportunities are optional and do not systematically focus on spatial ability, limiting their impact on instructional practices.

In Sweden, collective PCK is shaped through teacher autonomy and collaborative planning. Weekly departmental meetings provide a platform for curriculum interpretation and instructional refinement, and teachers engage in peer observation and interdisciplinary discussions. However, because spatial ability is not explicitly defined in the curriculum, its inclusion depends on individual teacher initiative rather than systemic support. While some teachers actively integrate spatial ability into Mathematics education through hands-on and visual tasks, others overlook it, leading to inconsistencies in spatial instruction across schools.

While some teachers develop effective strategies for incorporating spatial ability into their instruction, others lack the knowledge or tools to do so. This

aligns with findings in Papers B–D, which argue that teacher discretion in Sweden's curriculum results in highly variable student experiences, depending on whether teachers recognise spatial ability as an essential capacity.

This inconsistency poses a challenge. Paper A suggests that curriculum flexibility alone does not guarantee equitable access to spatial ability instruction. Without structural support, students may receive uneven exposure to spatial ability development opportunities. A more structured approach, where spatial ability is explicitly defined in subject curricula, would reduce the burden on teachers to determine its relevance on their own.

To address this challenge, the 2×3 and 3×3 frameworks from Papers C and D, as well as Malkogeorgou and Lin' (2024) actionable guidelines, offer practical tools for integrating spatial ability into teacher education. These frameworks provide structured guidance for teachers who may not know where to begin when incorporating spatial ability into the national curriculum. By embedding these frameworks in teacher education and professional development, educators can develop a more consistent and systematic approach to spatial ability instruction, ensuring that students across different educational settings receive equitable opportunities to develop this critical skill.

4.4. Microsystem: Classroom Pedagogy and Student Engagement

At the microsystem level, classroom instruction and student engagement play a crucial role in determining whether spatial ability is effectively developed through daily learning experiences. Paper A emphasises that while spatial ability is recognised as essential for STEM education, many teachers lack structured guidance and pedagogical confidence to integrate it into everyday instruction. As a result, spatial ability is often confined to Geometry rather than being developed through interdisciplinary, real-world application.

Paper E reinforces this issue, showing that during interviews, teachers frequently associated spatial ability with Geometry, reflecting a narrow conceptualisation that limits its application across different subjects. Paper D further illustrates how this limited perspective restricts students' exposure to spatial ability development in non-STEM subjects. While subjects such as Social Sciences potentially support spatial ability development, these connections are rarely made explicit in curriculum guidelines or teacher training, leading to missed opportunities for interdisciplinary learning.

Findings from Papers B–D highlight that Sweden's national curriculum treats spatial ability as an implicit skill rather than a mandated competency. Without formalised expectations, student engagement depends on teacher interpretation, leading to variability in classroom pedagogies. While some classroom pedagogies emphasise hands-on spatial ability tasks, offering students practical experiences, others rely on more theoretical, indirect methods, which may not be as effective in developing spatial ability.

Paper D suggests that students should engage with multiple visual components and knowledge types when working with spatial ability activities. However, its effectiveness depends on teachers' explicit awareness of spatial ability development. Subjects that naturally incorporate diverse visual elements (e.g., Geography and Mathematics) tend to have a greater impact on spatial ability development. In contrast, subjects like Civics, History, and Religion may only indirectly support spatial ability development—unless teachers make intentional connections in the classroom pedagogy.

The microsystem findings align with concerns raised by Geiser et al. (2008) and Sorby et al. (2018), who highlight the long-term impact of delayed or uneven exposure to spatial ability development on student confidence and performance. These studies stress that early and structured engagement is essential, as spatial ability does not develop uniformly without intentional support. This thesis shows that when spatial ability is introduced only implicitly or later in schooling, particularly in non-STEM subjects, students may miss critical developmental opportunities.

To address these challenges, the 2×3, 3×3 frameworks, and the actionable guideline serve as practical tools for teachers and teacher educators. These frameworks help educators identify, transform, and integrate various knowledge components into their teaching practices, ensuring that spatial ability development is intentional rather than incidental. By actively transforming knowledge components, such as from conceptual to procedural knowledge, teachers can enhance student engagement and facilitate deeper spatial ability development.

Paper E adds additional layer of complexity to student engagement. It examines how teacher perceptions of gender and student efficacy influence spatial ability development. Both Irish and Swedish teachers report perceiving gender disparities in spatial ability performance. They noted that male students are often encouraged more and provided with greater opportunities for spatial ability tasks, while female students are less likely to receive the same

level of encouragement or be steered toward spatially demanding subjects. To counteract these issues, early and systematic integration of spatial ability across subjects is essential. Rather than delaying spatial ability development until later school years, educational policies should introduce spatial ability development in early education to prevent gaps in confidence and engagement.

4.5. Limitations and Future Direction

This thesis acknowledges several limitations arising from both methodological choices and the scope of inquiry.

First, in analysing the Swedish curriculum, the English translation of the policy documents was used instead of the original Swedish version. While the use of English was intended to make the research accessible to a broader international readership, it may introduce interpretative gaps due to potential nuances lost or altered in translation. This choice could affect the precision of curriculum analysis, as certain meanings embedded in the original language may not be fully captured.

Second, the 2×3 and 3×3 frameworks used to interpret spatial ability within the curriculum were developed inductively through bottom-up analyses of policy documents, rather than derived from established constructs commonly cited in previous research, such as spatial visualisation or orientation. Although this approach may be viewed as unconventional within the broader spatial ability literature, it was purposefully adopted to interpret the national curriculum from the perspective of educators and policymakers, rather than imposing an external researcher lens. By working from the familiar language and structure of existing curricula, the frameworks aim to raise awareness of how spatial ability is already embedded in practice, thereby supporting educators in recognising and valuing this dimension of learning.

Third, the thesis primarily employs a qualitative methodology informed by an interpretivism paradigm. While this approach is well-suited for examining complex educational contexts, it inherently limits the generalizability of findings. Nevertheless, the objective was not statistical generalisation but analytical transferability. Rich contextual descriptions of participants and research settings are provided to support readers in assessing the relevance of the findings to their own contexts (Carminati, 2018; Shenton, 2004).

Fourth, the analysis centres on identifying potential opportunities for developing spatial ability in policy documents, without assessing how these

opportunities are implemented in classrooms or their effects on student learning outcomes. As spatial ability is not explicitly addressed in either the Swedish or Irish national curricula, its integration depends heavily on teachers' interpretations and enactment. This thesis does not evaluate the fidelity of implementation or observe pedagogical practices in classrooms.

To advance the findings of this thesis, several directions for future research are recommended.

First, future studies should consider conducting parallel analyses using both original-language and translated curriculum documents to better capture linguistic and conceptual nuances that may affect interpretation. This approach would help verify findings across multilingual contexts.

Second, future research could focus on empirically validating and refining the 2×3 and 3×3 frameworks by comparing them with established spatial factors, such as spatial visualisation, orientation, and mental rotation, in both policy and classroom settings. This would help bridge curriculum-based interpretations with psychometric and cognitive perspectives, offering a more integrated model for understanding and supporting spatial ability development in practice.

Third, the inductively developed 2×3 and 3×3 frameworks could be systematically applied to additional national curricula. Doing so would allow researchers to explore how spatial ability is embedded across diverse policy environments and whether consistent patterns or culturally specific practices emerge.

Finally, complementing the qualitative design of this thesis with quantitative studies could help examine spatial ability development at scale. For instance, survey-based or observational research could assess how curricular opportunities are enacted in classrooms and linked to measurable student outcomes.

5. Contribution to Knowledge Field

This thesis contributes to spatial ability research in four main ways.

First, it addresses a gap in the literature by focusing on curriculum policy and teacher practice—two areas that play a critical role in shaping how spatial ability is supported in education, but which have received limited attention compared to psychometric testing or intervention-based studies.

Second, it introduces the 2×3 and 3×3 frameworks as practical tools for identifying where spatial ability can be developed within curriculum documents. Unlike models based on cognitive traits, these frameworks are grounded in the structure and language of national curricula. This allows educators and policymakers to recognise existing opportunities for spatial learning and apply them in subject-specific teaching.

Third, by adopting an interpretivist paradigm, this thesis complements the predominantly positivist and post-positivist spatial ability literature, which has largely focused on measurement and intervention. It contributes a more nuanced understanding of how spatial ability development is interpreted and enacted by teachers in everyday educational practice.

Finally, the cross-national comparison provides new insights into how the interaction between curriculum policy, structural design, and teacher autonomy shapes the presence and implementation of spatial ability in education. This contribution extends the field's understanding beyond individual classrooms and offers a foundation for future research that engages with broader policy contexts and international perspectives.

The following section synthesizes the key findings from the appended papers and demonstrates how they collectively address the core research questions of this thesis.

1. How is spatial ability represented and structured within the national curriculum?

- Recognition varies across countries: Spatial ability is explicitly addressed in Ireland's curriculum, while in Sweden, Latvia, and the Netherlands, it remains implicit—often assumed to emerge through subjects like Mathematics and Science without formal definition. In Sweden, its presence is limited to brief mentions in subjects such as Art and Social Studies.
- Delayed emphasis in Sweden: Despite evidence supporting early spatial development, Sweden introduces spatial ability only in later stages of compulsory education, potentially missing key developmental windows.
- Lack of cohesive integration: Across countries, the absence of clear policy guidance leads to fragmented implementation, leaving the inclusion of spatial ability largely to individual teacher judgement.
- Tension between structure and autonomy: Ireland embeds spatial ability in its curriculum but limits teacher flexibility due to assessment pressures. Sweden offers more autonomy but lacks structured support, leading to inconsistent emphasis on spatial development.
- Underused interdisciplinary potential: The 2×3 and 3×3 frameworks highlight how spatial ability could be embedded across subjects. However, this potential remains underutilised, with limited cross-disciplinary integration in practice.

2. How do teachers perceive and implement the role of spatial ability within the national curriculum?

- Narrow conceptualisation: Teachers often associate spatial ability primarily with Geometry, limiting its integration across other subjects and restricting interdisciplinary applications.
- Varied implementation: National differences influence practice. In Ireland, structured training exists but system constraints limit flexibility. In Sweden, greater autonomy results in inconsistent and subjective interpretations of spatial ability.
- Professional development gaps: Spatial ability receives limited attention in teacher training. In Ireland, it is underemphasised despite formal

provision. In Sweden, it relies on informal peer collaboration without consistent guidance.

- Classroom variability: Teaching approaches differ widely. Some teachers use hands-on methods, while others take more abstract approaches, leading to uneven student access to spatial learning opportunities.
- Gender disparities: Teachers report that boys are more confident and more frequently encouraged in spatial tasks, while girls participate less. These perceptions may reinforce gender imbalances in spatial ability development.

6. Conclusion

This thesis investigated how spatial ability is represented in national curricula and experienced in teaching practices. Analysis of the Swedish curriculum revealed that spatial ability is not explicitly addressed but is embedded. The 2×3 and 3×3 frameworks developed by the appended papers provided systematic methods for locating these opportunities within policy documents. Teacher interviews further showed that in Ireland, although professional development has increased teachers' awareness of spatial ability, high-stakes assessment frameworks strongly influence classroom practices, often prioritising examinable objectives. In contrast, Swedish teachers, operating within a more autonomous and flexible curriculum structure, face different challenges related to curriculum interpretation and the implicit nature of spatial ability expectations. Overall, the findings highlight the need for a coordinated approach that aligns curriculum design, teacher knowledge, and policy structures to support the meaningful development of spatial ability in educational settings.

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Appendix A. Glossary of Terms

I

Interdisciplinary education

An approach to learning that integrates concepts, methods, and perspectives from multiple disciplines to provide a comprehensive understanding of complex topics.

N

National curriculum/curricula

A written document established by a government or education authority that outlines learning objectives, subject content, and assessment standards for formal education. It ensures consistency across schools and aligns with national educational policies and goals.

S

Spatial ability development

The natural or guided enhancement of spatial ability through education, experience, and exposure to spatial tasks. Unlike spatial training, it does not require a structured program but can occur in both formal and informal learning settings, influenced by instructional methods and curriculum design.

Spatial concepts

Core ideas about position, direction, distance, shape, and spatial relationships are used to interpret and navigate space (National Research Council, 2006).

Spatial factors

Cognitive dimensions involving the ability to perceive, manipulate, and reason about spatial relationships, underpinning skills such as visualisation, orientation, and rotation, etc.

Spatial task

An activity that involves spatial information processing and may require visualisation, manipulation, spatial reasoning, and hand-motor coordination.

Spatial information

Data related to shapes, positions, paths, and spatial relationships between objects within a given reference frame.

Spatial relationship

The relative position, distance, direction, or orientation of objects in space and how they interact with one another within a given reference frame.

Spatial training

A structured method for enhancing spatial ability through targeted exercises, improving capacities such as spatial visualisation, mental rotation, and reasoning within formal or informal education settings.

Appendix B. Code definitions and examples.

Codes	Definitions	Example (Subject and the curriculum content)
Graphical-conceptual	Two-dimensional visual representations—such as symbols, diagrams, or graphs—that depict the structure, organisation, or construction of an entity. Interpreting this content requires conceptual understanding and may involve factual, cultural, or historical knowledge related to the entity depicted.	Mathematics Basic geometric two-dimensional objects and the objects sphere, cone, cylinder and cuboid (Skolverket, 2024, p.58)
Graphical-procedural	Two-dimensional visual representations—such as symbols, diagrams, or graphs—that depict the structure, organisation, or construction of an entity. Interpreting this content requires procedural understanding and involves carrying out hands-on activities to reach a solution to a problem.	Chemistry The structure of matter visualised using simple particle models (Skolverket, 2024, 169).

Codes	Definitions	Example (Subject and the curriculum content)
Graphical-spatial citizenship	Two-dimensional visual representations—such as symbols, diagrams, or graphs—that depict the structure, organisation, or construction of an entity. Interpreting this content requires understanding how to convey spatial information that enables participation in societal and civic contexts.	Geography Causes and consequences of demographic patterns and changes: population distribution, population trends, migration patterns and urbanisation (Skolverket, 2024, p.223)
Pictorial-conceptual	Two-dimensional visual representations—such as pictures and materials—that include both schematic and aesthetic features (e.g., colour, texture). Interpreting this content requires conceptual understanding and may involve factual, cultural, or historical knowledge related to the entity depicted.	Crafts Metal, textiles and wood. Properties and uses of materials (Skolverket, 2024, p.38).
Pictorial-procedural	Two-dimensional visual representations—such as pictures and materials—that include both schematic and aesthetic features (e.g., colour, texture). Interpreting this content requires procedural understanding and involves carrying out hands-on activities to reach a solution to a problem.	Science (for years 1-3) Performing and documenting the investigations with words, images and digital tools (Skolverket, 2024, p.162).
Pictorial-spatial citizenship	Two-dimensional visual representations—such as pictures and materials—that include both schematic and aesthetic features (e.g., colour, texture). Interpreting this content requires understanding how to convey spatial information that enables participation in societal and civic contexts.	Languages learning—Swedish Fiction for children from different times and different parts of the world. Songs, oral narration, picture books, chapter books, lyrical poetry, drama, fairy tales and myths (Skolverket, 2024, p.244).
Manufactured-conceptual	Three-dimensional entities—such as handicrafts or artefacts—that combine graphical and pictorial elements to represent conceptual knowledge.	Languages learning—Sami Sami cultural heritage in various forms, such as games, music, handicraft and other

Codes	Definitions	Example (Subject and the curriculum content)
	Interpreting this content requires conceptual understanding and may involve factual, cultural, or historical knowledge related to the entity depicted.	forms of aesthetic expression (Skolverket, 2024, p.190).
Manufactured-procedural	Three-dimensional entities—such as handicrafts or artefacts—that combine graphical and pictorial elements to represent conceptual knowledge. Interpreting this content requires procedural understanding and involves carrying out hands-on activities to reach a solution to a problem.	Technology The pupils' own constructions using mechanisms, electrical connections and strong and stable structures (Skolverket, 2024, p. 269).
Manufactured-spatial citizenship	Three-dimensional entities—such as handicrafts or artefacts—that combine graphical and pictorial elements to represent conceptual knowledge. Interpreting this content requires understanding how to convey spatial information that enables participation in societal and civic contexts.	Art Fine art pieces, documentary art and architecture from different times and cultures (Skolverket, 2024, p.33)

Note: The spatial attributes of the content are indicated by bold words.