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Review

A Global Overview of SVA—Spatial–Visual Ability

Shweta Tiwari [1], Bhavesh Shah [1] and Arunachalam Muthiah [2,*,†]

[1] Department of Interior Design, Karnavati University, Gandhinagar 382422, India; shwetatiwari21@karnavatiuniversity.edu.in (S.T.)

[2] Research Institute of Engineering and Technology, Hanyang University ERICA, Ansan-si 15588, Republic of Korea

* Correspondence: arunachalam@hanyang.ac.kr or arunmuthiah8@gmail.com or arunachalam@gnu.ac.kr; Tel.: +82-010-5289-7864

† Previous Affiliation: Engineering Research Institute, Gyeongsang National University, Jinju 52725, Republic of Korea.

Abstract: This study examines the global literature that looks at spatial–visual abilities (SVA) while considering the numerous differential studies, methods of evaluation designed over a century, and multiple external influences on its development. The dataset was retrieved from Google Scholar and publisher databases such as Elsevier, Taylor & Francis, Springer, etc. Only factual reports and bibliographic reviews were included in an analysis of a total of 87 documents. Each study of SVA is classified based on information, country, year, and age groupings. SVA has been extensively studied in the areas of "STEM (Science, Technology, Engineering and Mathematics) fields", "demographic factors" and "other activities". "Spatial visualisation" or "visual ability" is the term employed to refer to the cognitive ability that allows one to comprehend, mentally process, and manipulate three-dimensional visuospatial shapes. One of the most crucial distinct abilities involved is spatial aptitude, which aids in understanding numerous aspects of everyday and academic life. It is especially vital for comprehending scientific concepts, and it has been extensively studied. Nearly all multiple-aptitude assessments include spatial ability. It is determined that over the past two decades, the study of SVA has gained momentum, most likely because of information being digitised. Within the vast reservoir of spatial-cognition research, the majority of the studies examined here originate from the United States of America, with less than a quarter of the studies based in the Asia–Pacific region and the Middle East. This paper presents a comprehensive review of the literature on the assessment of SVA with respect to sector, year, country, age and socio-economic factors. It also offers a detailed examination of the use of spatial interventions in educational environments to integrate spatial abilities with training in architecture and interior design.

Keywords: spatial–visual ability; interior design; demographic factors; assessment tools; design education

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1. Introduction

Research on mechanical aptitude and practical ability has contributed to the identification of spatial aspects, which assess an individual's skill in understanding spatial relationships [1]. A significant amount of study during World War II confirmed that spatial ability is a key aspect of intelligence, encompassing skills such as visualisation, perception, relations, orientation, and mental rotation [2,3].

"Spatial visualization is the ability to mentally rotate, manipulate, and twist 2D and 3D stimulus objects", as stated by Mark G. McGee in Human spatial abilities: Psychometric Studies and Environmental, Genetic, Hormonal, and Neurological Influences, September 1979.

Psychometric research seeks to identify determinants of spatial ability, whereas studies on development aim at comprehending the manner in which this ability evolves in children, taking into account neurological and environmental effects, especially in relation to gender differences [2].

Spatial abilities are thoroughly examined in STEM [4] and in various disciplines like aeronautics, technical drafting programs, etc. [5], strongly correlating with performance in relevant courses and accomplishments. Initiatives [4] have demonstrated beneficial impacts on STEM academic achievement.

The cognitive capacity to comprehend, mentally process, and manipulate three-dimensional visuospatial shapes is termed "spatial visualisation ability". Encoding a visuo-spatial stimulus, creating a visuo-spatial image from perceptual information, mentally rotating an image, changing one's point of view, and equating a visual stimulus to an image in working memory are all part of spatial visualisation [6].

Spatial visualisation skills involve understanding and mentally altering three-dimensional forms. In disciplines such as interior design and architecture, designers depend on visuospatial-processing abilities to envision places, considering scale, relationships, and human interactions, as cited in [5] by Castro-Alonso & Atit, 2019. These processes depend on spatial–visual processing, which entails the comprehension and conversion of 2D and 3D spatial information and is also known as spatial–visualisation ability (SVA) [5].

With more than half of the research originating from the United States of America, there is a dearth of studies on spatial-visualisation ability in Europe, and especially in the Asian and Middle Eastern nations. This distorted portrayal results in an inaccurate presentation of facts and figures in the existing body of literature. This study attempts to bridge this void and demonstrate the need for any subsequent research to be inclusive of the worldwide audience. Very few studies examine cognitive abilities from the perspective of the developmental stages of an individual. The literature presented here was categorized by the subjects' age to assist audience in following the data from early childhood to adolescence and adulthood, emphasizing the nuances of each phase of growth. Given the long-standing system of education, the age-group categories mirror the phases of growth. To reflect lifelong changes, this overview employs a developmental perspective.

2. Rationale behind the Study

Study in the realm of spatial skills has been consistent throughout the last century and has proved to be a determinant of success in science and technology fields [7]. Spatial visualisation has been deemed an integral ability for engineers, scientists, and even artists [8], with architects and interior designers relying heavily on this skill to conceptualize and create innovative built forms. The aforementioned ability goes beyond simply picturing objects in space; it comprises mental rotation, observation of perspective, and the capacity to comprehend and control intricate spatial connections. Strong spatial skills are associated with academic achievement in disciplines such as computation, engineering, and mathematics because they make individuals better able to solve problems and design solutions that require spatial reasoning [9]. Consequently, educational environments have placed a greater emphasis on spatial ability, with initiatives designed to cultivate and improve these capabilities in students in order to equip them for prospective careers in STEM.

It is imperative to examine the effects of external influences such as family socioeconomic status on cognitive abilities, brain volume, and the features of neural tissue. Psychological characteristics and general well-being are determined by parental education and parental assets [10,11].

At present, there is a lack of comprehensive studies that target students of architecture and interior design beyond undergraduate studies [12]. Subject to development and directives, spatial ability is adaptable. This necessitates the development of a domain-specific evaluation of spatial ability and a critical examination of the elements underlying the spatial skills required in interior design. Therefore, design educators should foster students' capacity to extend visualisation from 2D to 3D when they are teaching design communication [13].

A comprehensive investigation of the process is required to comprehend the category of spatial thinking distinct to architecture and design; this understanding will lead to curriculum changes and benefit novice students of architecture and design [12]. Incorporating computer-aided design (CAD) and virtual-reality (VR) technologies into the curriculum can improve students' spatial abilities [3,14–17]. Educational institutions can overcome the divide between academic competence and practical application by ensuring students comprehend and employ theoretical concepts. This integrative approach equips students for the evolving needs of the architectural and interior-design professions.

3. Constructs of Spatial–Visual Ability

The term "spatial ability" has been defined as *"skill in representing, transforming, generating, and recalling symbolic, non-linguistic information"* by Marcia C. Linn and Anne C. Peterson in Emergence and Characterisation of Sex Differences in spatial ability: A Meta-Analysis, Child Development, Wiley-Blackwell, Society for Research in Child Development, 1985.

Ref. [1] addressed the factors that contribute to disparities in performance on tests of spatial ability, encompassing environmental, genetic, hormonal, and neurological aspects. Gender disparities in perceptual-cognitive functioning arise from variances in spatial perception and orientation capacity. Neurological studies offer clinical substantiation for the framework of differences in spatial ability, specifically in regard to handedness and brain lateralisation for spatial and language processing.

A China-based study [10] that examined the correlation between socioeconomic status (SES) and brain anatomy, primarily focusing on grey-matter volume (GMV) and white-matter integrity (measured by fractional anisotropy, FA), concluded that SES is positively associated with greater cognitive abilities. It also found that females from higher-SES families have imaging results that indicate an increased level of neural tissue, such as higher FA and lesser mean diffusivity (MD). In contrast, males display the reverse patterns.

The categorisation of spatial ability has been inconsistent and indeterministic across literature. Over the years, spatial abilities have been renamed several times by academicians and researchers alike. The prefix "spatial" remains constant, whereas the suffix "ability" has been interchanged with "cognition, reasoning, skill, reasoning, perception, etc.". The configuration of spatial ability vary by researcher based on their domain of study [13].

On the basis of the abundance of factor-analysis studies done since the 1930s, two distinct spatial abilities, "visualisation" and "orientation", were identified [1]. Mark G McGee definesSpatial–visual spatial–visualisation "as the ability to mentally rotate, manipulate, and twist two- and three-dimensional stimulus objects" and spatial orientation "as the ability that includes the comprehension of the arrangement of elements within a visual stimulus pattern, the aptitude to remain unconfused by the changing orientations in which a spatial configuration may be presented, and an ability to determine spatial orientation with respect to one's body" [1,13].

Spatial information comprised of shapes, locations, paths, and relationships amongst them is portrayed in human cognition and can be mentally manipulated to construct and navigate the physical entity, an ability that ultimately leads to successful academic and intellectual endeavours. A distinction between spatial representations is driven by a range of cognitive, neurological, and linguistic concerns: (1) those that are *"intrinsic"* to objects—their shapes and form-based representation—and (2) those that are *"extrinsic"*—relationships between and among objects and frames of reference [18].

Ref. [19] proposed three distinct subconstructs of spatial ability based on a meta-analysis of studies conducted from 1974 to 1982: (1) mental rotation—the ability to rotate a 2D or 3D figure/object swiftly and precisely (p. 1483); (2) spatial visualisation—the ability to manipulate complicated spatial information in multiple steps; and (3) spatial perception—the ability to identify spatial relationships with respect to the orientation of one's own body, despite the presence of distracting information.

D. Kimura (2000), as cited by [20], identified six spatial parameters that are widely accepted because they can be clearly distinguished by experimental measurement: *"spatial orientation, spatial location memory, targeting, spatial visualization, dis-embedding and spatial perception"*. As a multifaceted capacity, spatial ability comprises several subconstructs. Several studies of spatial ability have reached consensus on three subconstructs, irrespective of the multidimensional character of spatial ability, which can be categorised in a plethora of ways, though the nomenclature might vary slightly. The three subconstructs are mental rotation (MR), spatial–visualisation (SV), and spatial perception [5,19].

Interior design and architecture are fundamentally problem-solving processes in one form or another. As such, spatial design necessitates the synthesis of spatial cognition with the design process involved in creative problem-solving. Furthermore, Linn & Peterson (1985) noted that the strategies required to solve spatial-visualisation problems may or may not include mental rotation and spatial perception; the former two involve "single-solution strategies", whereas spatial–visualisation allows for the possibility of "multiple-solution strategies".

In lieu of developing a domain-specific (for interior design) tool for assessment of spatial ability with all-inclusive credibility, reliability, and environmental information, Joori Suh and Ji Young Cho [5] focused on two subconstructs—mental rotation (MR) and spatial–visualisation (SV), omitting spatial perception since it requires one to move and navigate using their body, making it difficult to identify [19]. They defined mental rotation (MR) as *"the ability to mentally rotate 3D spatial forms and visualize them rapidly"*. Spatial–visualisation was further expanded into three types on the basis of various visualisation modes frequently utilised in spatial-design representation and interpretation: (1) SV I.A (2D 3D)—*"the ability to read 2D information and convert it into 3D and find correct location for the correct viewpoint with respect to the orientation of the test takers' own bodies"*; (2) SV I (2D to 3D)—*"the ability to read 2D information (floor plan drawings) and expand it into volumetric forms, mentally trying out various possibilities"*; and (3) SV II (3D to 2D)—*"the ability to read volumetric information and translate it into 2D and find the correct location for the viewpoint by compressing complex volumetric information and converting it into 2D information"*. These subconstructs were verified following extensive revisions between 2012 and 2021, with comprehensive findings over the years.

For the purpose of this study, the above subconstructs as defined by Joori Suh and Ji Young Cho in multiple studies published by them [5,13,21,22], were used as the foundational framework for further investigations.

4. Materials and Methods

4.1. Searching for Information

For the purpose of this study, the Google Scholar database was used to search for and categorize relevant research articles. Global publications like Elsevier, Taylor & Francis, Springer, etc., were accessed via Karnavati University's license/account. A search was carried out to gather all the research that referenced "Spatial Visualisation", "Visual Ability", "Spatial Visualisation Assessment", "Spatial Visualisation Test", "Visual Ability Assessment", or "Visual Ability Test". Emphasis was placed on articles that discussed (1) the construct of spatial visualisation ability (understanding the multiple components within spatial–visual abilities), (2) existing assessment tools for spatial–visual ability; (3) influence of demographic factors (socioeconomic, educational and gender), and (4) influence of age on spatial–visual ability.

Of the collected informative articles, those in certain formats including magazines, newspapers, webpages, etc., were discarded. The number of studies (only research articles and conference proceedings, which were considered as book chapters) that were finally selected for this document was 87. Several articles were not considered because they were republished papers, either as reprints or articles from conferences that were afterwards published in journals. Only original articles were taken into consideration.

4.2. Data Analysis

The table below (Table 1) lists the variables and categories and their acronyms. Additionally, all journals were taken into account.

Table 1. Variables, categories, and abbreviations.

Variable	Categories	Abbreviation
Sector	STEM (Science, Technology, Engineering and Mathematics), geometry and geography	A
	Socioeconomic Factors, Demographics and Gender Differences	B
	Architecture, Interior Design, Product Design and Design	C
	Computer Graphics, Computer Games, Google SketchUp, VR and AR	D
	Development of a new assessment tool	E
	Literature Studies	F
	Psychology, Intelligence, and individual differences	G
	Mental Rotation and Mental Cutting	H
	Biology and Neurology	I
	Other	J
Year	Articles published in and before the 1970s	Y1
	Articles published in the 1980s	Y2
	Articles published in the 1990s	Y3
	Articles published between 2000 and 2005	Y4
	Articles published between 2006 and 2010	Y5
	Articles published between 2011 and 2015	Y6
	Articles published between 2016 and 2020	Y7
	Articles published from 2021 onwards	Y8
Country	America: Canada, Mexico, Peru and USA	C1
	Europe: Austria, France, Germany, Hungary, Ireland, Italy, Netherlands, Portugal, Romania, Slovenia, Sweden and Switzerland	C2
	Asia: China/Hong Kong, India, Indonesia, Israel, Japan, Malaysia, Saudi Arabia, South Korea, Taiwan and Turkey	C3
	Australia	C4
Age Group	5 years and below—kindergarten students and children	A1
	6 years old to 8 years old—-primary-school students	A2
	9 years old to 15 years old—middle- and high-school students	A3
	16 years old to 17 years old and up-to 17 years—higher-secondary-school students	A4
	18 years old to 22 years old—university and graduate students	A5
	23 years old and above—postgraduate students and working professionals	A6
	Mixed-age groups	A7
	Age not applicable	A8

To make organizing information easier, the sector categories, countries, years, and ages were aggregated. Continents were used to classify the countries. Only those countries where the SVA has been studied are shown in the table.

The 87 studies finally selected, however, were categorized by sector, year, country, and age group. A customized categorisation was employed for the overall sector grouping. Within each sector, further categories were established for additional clarity and organisation, however in this instance, the information was derived from the research articles that were analysed.

The literature was categorised age-wise, which enables readers to track the evolution of research findings from early childhood to the teenage years, adulthood, and subsequent stages of life, emphasizing the subtleties and intricacies that emerge during each period of development. As the frameworks of the educational system are well-established, the age groupings have been made according to the commonly recognised developmental phases (Table 1). This overview employs a developmental framework, recognizing the significant variations in human experiences, behaviours, and consequences that occur throughout distinct periods in life.

5. Results

Table 2 provides the frequency distributions for each category of variable.

Table 2. Frequencies of each category.

Variable	Category	Frequency	Percentage—%
Sector	A	8	9.19
	B	8	9.19
	C	7	8.04
	D	6	6.89
	E	5	5.74
	F	7	8.04
	G	3	3.44
	H	0	0
	I	0	0
	J	2	2.29
	A + B	9	10.34
	A + C	1	1.14
	A + D	1	1.14
	A + E	2	2.29
	A + G	4	4.59
	A + E + G	1	1.14
	B + C	3	3.44
	B + D	4	4.59
	B + I	2	2.29
	B + H	3	3.44
	B + C + E	1	1.14
	B + E + F	1	1.14
	C + D	2	2.29
	C + E	3	3.44
	E + G	3	3.44
	E + F	1	1.14
	G + H	1	1.14
Year	Y1	3	3.44
	Y2	5	5.74
	Y3	6	6.89
	Y4	13	14.93
	Y5	18	20.68
	Y6	13	14.93
	Y7	17	19.53
	Y8	12	13.78
Country	C1	46	52.85
	C2	5	5.74
	C3	19	21.83
	C4	13	14.93
	C1 + C2	2	2.29
	C1 + C3	2	2.29
Age Group	A1	2	2.29
	A2	3	3.44
	A3	5	5.74
	A4	4	4.59
	A5	39	44.81
	A6	6	6.89
	A7	15	17.23
	A8	13	14.93
		87 [1]	100

[1] A total of 87 research articles were considered for this study.

Among the research articles studied, Spatial–visualspatial–visualisation ability has been examined most in the sector of "STEM, geometry and geography; and Socioeconomic factors, Demographics and Gender Differences (A + B)—10.34%", which is followed by "Socioeconomic factors, Demographics and Gender Differences (B)—9.19%" and "Architecture, Interior Design, Product Design and Design (C)—9.19%". Among the 87 research articles reviewed, 42 studies were conducted in two or more sectors, which is also denoted in Table 2.

In the earliest studies on spatial–visual abilities were conducted in 1979, wherein they were identified and defined by M. G. McGee as "the ability to mentally rotate, manipulate, and twist two- and three-dimensional stimulus objects" [1]. However, the maximum number of studies was conducted between 2006 and 2010 (Y5) and in the following years, from 2011 onwards (Y6 and Y7), as evident by the numbers in Table 2; the definition and the construct of "spatial skills" as an umbrella term have evolved extensively, as have their applications and relevance in the field of cognitive abilities.

Notably, more than half of the studies were carried out in America (C1)—52.85%. There is a deficit of research on Spatial–visualspatial–visualisation ability, especially in the European and Asian countries, as presented in Table 2. This skewed representation results in biased information and data representation, suggesting that future research directions should be inclusive of the global populace.

Also evident from the below table is that nearly all the studies were conducted on subjects aged 18 to 22 years old (A5—university and graduate students; 44.81%), followed by studies with mixed-age groups (A7; 17.23%) and studies that did not consider the age of the participants or did not focus on participant-based investigation (NA; 14.93%). Only approximately 16.08% of the studies (A1 + A2 + A3 + A4) concentrate on age groups below 18 years, for whom the developmental research is significant.

5.1. Analysis by the Age Categories and Assessment Tools

5.1.1. Ages 5 Years and Below—Kindergarten Students and Children (A1)

Table 3 reflects that only a handful of studies were conducted on children below the age of 5 years.In one of the earlier studies from the year 1985, which specifically focused on individual differences and the capacity for mental rotation, a stimulus was mentally rotated a certain number of times for forty 3- to 4-year-old kids, who were subsequently then tasked with selecting the stimulus' appearance from a variety of options. Data showed that children had trouble identifying reflections, a task that is very similar to the yes/no option in prototypical rotation research, and there was a significant effect for the quantity of orientation signals. The findings raised concerns regarding the application of the paradigm for research in child imagery because they imply that 'initial recognition of the orientation differences between two figures' and 'a judgement of equivalence' may be difficult for these participants [23]. One of them, in the field of mathematics and intelligence, employed a combination of a variety of tasks, namely the Woodcock-Johnson III Test of Achievement, Forward Digit Span and Reverse Digit Span, Head-Thigh-Toes, and Test of Visual Perceptual Skills—Revised". This study was developed by Wing Kai Fung, Kevin Kien Hoa Chung and Chun Bun Lam to examine the bidirectionality among Chinese kindergarten children's mathematics, executive function and visual–spatial skills. This study concluded that visual–spatial skills might prove more significant than executive functioning in predicting children's mathematical achievement [24].

5.1.2. Ages 6 Years to 8 Years—Primary-School Students (A2)

As shown in Table 4, the 2015 study in this age group overlapped the three sectors of geoscience, individual differences, and the development of a new assessment tool. To ascertain the presence and extent of flexibility in spatial abilities, the authors, Nora S. Newcombe and Thomas F. Shipley, carried out a significant meta-analysis in 2015. Instead of using an inductive method and factor analysis, this study presents a typology for thinking about the structure of spatial intelligence that originates from the investigation of the nature of spatial thinking. Within this distinct typology, novel approaches to assessments are also highlighted [18].

Table 3. Ages 5 years and below—A1.

Reference	Country	Year	Age	Sector	Objective
[23]	USA	1985	3–4 years	G + H	Examination of young children's ability to discriminate reflections and rotations of visual stimuli within the confines of a mental-rotation task.—MRT
[24]	China/Hong Kong	2020	Kindergarten children	A + G	Investigation of bidirectionality among Chinese kindergarten children's mathematics, EF (executive functioning) and VS (visual–spatial skills).—MRT

Table 4. Ages 6 years to 8 years—A2.

Reference	Country	Year	Age	Sector	Objective
[18]	USA	2015	Under 8 years	A + E + G	• Statistics on the malleability of spatial abilities based on a meta-analysis with its organisational structure. • Formulating assessments to measure skills in geoscience and individual differences.—SVA 2(3D to 2D) (OB) [2]
[17]	Indonesia	2023	5 to 8 years	D	• Design an educational game that strengthens cognitive abilities in children. • Aid preschool educator and parents in adopting educational simulations.—NA
[25]	Germany	2024	Kindergarten children	B	• Explore implicit and explicit gender norms on child spatial ability. • Examine gender preconceptions and performance on a spatial task.—MRT

[2] OB—Object-based testing instruments.

An Indonesia-based study [17] developed an educational game, "DINO vs. DINI", to enhance the cognitive abilities of children, equipping them for elementary education. This game incorporates sections that focus on pictorial guessing, colour recognition, word completion, and counting. It is designed to facilitate successful teaching and engage children's attention. By using simulation-based learning, this game helps educators and parents move to more interactive and immersive learning. Furthermore, they ignite children's eagerness for cognitive growth.

In 2024, a German study employed an implicit-association task, a poll on explicit stereotypes, and a chronometric mental rotation task to evaluate gender stereotypes in preschoolers. They study discovered that boys demonstrated stronger stereotypes linking spatial ability with their gender compared to girls [25].

5.1.3. Ages 9 Years to 15 Years—Middle- and High-School Students (A3)

Table 5 states in the domain of geometry, the investigation of student spatial–visual ability and gender analysis was conducted through a case-study approach in [26]. The study utilised the reflective questionnaire by Ramful, Lowrie, and Logan, 2017 as cited by [26], followed by a semi-structured interview of the participants and gender analysis of student spatial–visual abilities. The study used the categories of visualisation developed by Hegarty and Kozhevnicov, 1999, as cited by [26]. The findings indicated inadequate spatial–visual ability in students in geometry, especially in visual representation, with boys generally outperforming girls. In 2013, ref. [7] carried out a study to determine whether spatial ability could predict the integration and application of prior knowledge, along with the generation of new knowledge. This study employed a technique centred on group membership to investigate remote parameters and assess the construct reliability of psychometric tests. The selection criteria of the participants included a minimum score of 500 on the SAT-M (Scholastic Aptitude Test—Mathematics) and a minimum score of 430 on the SAT-V (Scholastic Aptitude Test—Verbal), which indicate the participants' cognitive ability to be in the top 0.5% for their age group. The significance of spatial ability for comprehending education and enhancing intellectual creativity in STEM areas was emphasized by the results. Ref. [7] suggests future research to examine the methods by which spatial ability supports original thinking and inventive output.

Table 5. Ages 9 years to 15 years—A3.

Reference	Country	Year	Age	Sector	Objective
[7]	USA	2013	13 years	A + G	Determining the potential of spatial ability, mathematical reasoning, and verbal reasoning for future psychological research and their role in differential development across the lifespan.—SVA 1 (2D to 3D)
[26]	Indonesia	2021	Grade 7 and junior-high-school students	A + B	Investigate the spatial cognition of students in geometry while differentiating between genders.—MRT
[27]	Spain	2017	11 years	B	Investigation of how various demographic factors, including parental education, gender, and family setup, impact children's cognitive aptitude assessment.—NA
[28]	Slovenia	2020	11–14 years	D	Examine the progress of SVA in students who underwent training in 3D modelling compared to a control group that did not undergo such training.—MRT, SVA 1 (2D to 3D)
[29]	Australia	2016	11–13 years	E	Derivation of a comprehensive measure of spatial ability, comprising mental rotation, spatial orientation, and spatial visualisation.—MRT, SVA 1 (2D to 3D), SVA 2 (3D to 2D) (OB)

A Spanish study [27] carried out on a group of 1008 children from the WISC-V normative sample utilised the WISQ-V FSIQ (Wechesler Intelligence Scale for Children—5th edition Full Scale Intelligence Quotient) and fundamental scores on indexes to evaluate the relationship between cognitive performance and the education level of parents, gender, and the make-up of the family. While gender was not a significant predictor of cognitive capacity, family structure had a minimal impact, with dual-parent families having children who obtained higher scores in comparison to single-parent families. The study found a notable correlation between the education level of parents and their children's cognitive capacity, wherein higher parent education levels were connected to higher cognitive capacity [27].

In order to determine how engineering 3D modelling with SketchUp affects students' spatial thinking and visualisation abilities, the study conducted by [28] adopted the experimental approach of empirical research in education. Several assessments, including the Differential Aptitude Test: Space Relations, the Picture Rotation Test, the Mental Rotation Test, the Form Board Test, The Punched Holes Test, The Surface Development Test, and the Purdue Spatial Visualisation Test: Rotations, were employed to gauge the students' spatial visualisation skills. The findings established that the incorporation of spatial modelling with SketchUp in early science and technology classes can enhance the spatial–visualisation abilities of children [28].

In 2016, authors Ajay Ramful, Thomas Lowrie, and Tracy Logan developed the SRI (Spatial Reasoning Instrument) to assess spatial-reasoning abilities, particularly in mental rotation, spatial orientation, and spatial visualisation, for both educational and cognitive purposes. Correlations were calculated to assess the alignment of the SRI with established spatial-reasoning instruments, including the CRT, CCT, and PFT by Ekstrom et al., 1976 and the SOT by Kozhevnikov and Hegarty, 2001, as cited by [29].

5.1.4. Ages 16 Years to 17 Years and up to 17 Years—Higher-Secondary-School Students (A4)

Table 6 showcases the studies conducted in the age-group of 16–17 years. In 1993, researchers Llyod G. Humphreys, David Lubinski and Grace Yao delved into the shortcomings of conventional measures, notably the Scholastic Aptitude Test (SAT) and the Graduate Record Examination (GRE), as tools to identify top-notch individuals in the fields of physical science and engineering. They undertook longitudinal studies on vast numbers of high school students who were monitored for 11 years after their graduation. The predictive validity of spatial–mathematical and verbal–mathematical ability composites was verified, and diverse educational and occupational groups were effectively identified [8].

Table 6. Ages 16 years to 17 years and up to 17 years—A4.

Reference	Country	Year	Age	Sector	Objective
[8]	USA	1993	Grades 9 to 12	A + G	Group-membership prediction can improve test-validation designs that are focused on individual differences in standard performance and the significance of SVA in STEM and creative disciplines.—NA
[16]	Malaysia	2008	MA [3] = 15.5 years	D	Examine the implications of a variety of training techniques for SVA enhancement among pupils of secondary school, along with the gender disparity in SVA enhancement and the relationship between training technique and gender.—MRT, SVA 1 (2D to 3D)
[30]	Italy	2006	13–17 years	E	Discussion of alterations to the testing instrument and examination of the findings to use them for evaluating the 3D spatial abilities of young learners.—NA
[31]	USA	1999	12–17 years	F	Facet Theory and Multidimensional Similarity Structure Analysis (SSA) was used to investigate the structure of spatial ability in exceptionally intelligent youth.—MRT, SVA 1 (2D to 3D), SVA 2 (3D to 2D) (OB)

[3] MA—Mean age.

An experiment conducted by [16] used stratified random sampling to assign 33 secondary school learners to experimental and control groups; the experimental groups were trained in interaction-enabled DVEST (Desktop Virtual Environment Spatial Trainer) and animation-enhanced DVEST, while the control group received traditional tutoring. The results of this experiment [16] emphasised the relevance of spatial visualisation skills in technical training and advised using digital resources such as iDVEST in order to assist students to enhance their spatial abilities.

An Italian study in 2006, demonstrates how established methods of assessment were modified to measure 3D spatial skills in young learners. The methods for developing the measures, as well as the basis for selecting and constructing the questions, are also included in the study. The findings implied that a latent spatial intelligence is assessed by different tests and that it is advisable to administer the currently developed test to a larger student population for further validation [30].

Authors Heinrich Stumpp and John Eliot utilized Facet Theory and Multidimensional Similarity Structure Analysis (SSA) to examine correlates of spatial ability performance. The findings suggested the pattern of spatial ability in academically gifted individuals is similar to that of more representative sample sizes, implying that the findings can be extended to larger sample sizes [31]. They recommended that additional studies be undertaken to determine the generalizability of the findings on the highlighted aspects of spatial ability in academically gifted students.

5.1.5. Ages 18 Years to 22 Years—University and Graduate Students (A5)

Table 7 shows the largest number of studies conducted in participants of age 18 to 22 years, typically university going students. Mental rotation is the most common ability within the subconstruct of spatial–visual ability that is tested within the domain of engineering—STEM, geometry and geography. All four studies conducted for this age group from the year 2013 to 2018 used either the Mental Rotations Test (MRT) [32] or the Revised Purdue Spatial Visualization Test: Visualisation of Rotations (PSVT:R) [33].

Authors Yukiko Maeda, So Yoon Yoon, Kin-Kang Gyenam and P. K. Imbrie [34] presented comprehensive and reliable psychometric data on the Revised PSVT:R as a suitable assessment tool for STEM fields based on scores collected from 2469 participants enrolled in the first-year engineering program at a public university in the United States. On the other hand, Petros Kastioloudis, Vukica Jovanovic and Mildred Jones [35] employed the Mental Rotations Test (MRT) to conclude that the capacity to visualise space is a crucial aspect of intelligence and vital for success in the engineering and technological professions. Eyüp Yurt and Vural Tünkler from Turkey observed a correlation involving spatial aptitude and scholastic achievement [36] and suggested long-term research aimed at the way potential teachers' spatial abilities evolve over time to identify effective techniques for improving them. In 2018, an inquiry conducted by Sheryl Sorby, Norma Veurink, and Scott Streiner deduced that remedial training in spatial skills improved first-year engineering students' academic performance, especially in STEM courses, and emphasised the need for further investigations to understand the lasting impacts of spatial-skills intervention on the professional prospects of engineering students [4]. The findings of a Portugal-based study [37] indicate that the use of Geographical Information Systems (GIS) is linked to enhanced spatial abilities in students, regardless of their cognitive ability, academic discipline, or gender; this result underscores the beneficial influence of GIS exposure on spatial–visual abilities.

Notably, studies examining this age bracket were associated seven published papers, the maximum number among studies of all age brackets, and they cover the domains of STEM, along with socioeconomic factors, demographics and gender differences equally. Of the two studies conducted in the 90s, ref. [38] established that the redesigned MRT [32] produces substantial, consistent gender differences affirming the original version; along with [39] who also confirmed that men demonstrated superior performance in mental rotation tasks, possessed better knowledge of geography as well as varied navigation tactics. Both of these studies employed MRT [32] as part of their methods. Two separate Europe-based studies conducted in the 2000s in the area of descriptive geometry that utilised MCT [40] as one of their methods concluded that that there were notable disparities, confirming a variation in spatial ability between the genders [41]; assessment of the participants at the start and conclusion of two academic semesters found significant improvement in spatial ability over this time [42]. Cheryl A. Cohen and Mary Hegarty verified the development of the Santa Barbara Solids Test (SBST) [43] a psychometric test of cross-sectioning capacity; this ability is vital for STEM fields, and the study indicated that on tasks that are challenging to analyse, men do better than women. A French study published in 2021 supported the premise that there exists a correlation between spatial visualisation and academic performance that includes 2D and 3D visual representations [9]. It employed the MRT [32], the MCT [40] and the Revised PSVT:R [33] to find that students with technical backgrounds scored better, while female students fell behind male students. Another Swedish research article [44] administered the Santa Barbara Sense of Direction Scale (SBSOD) [45] to measure spatial orientation and determined that males surpassed females in the test, with no differences according to the field of study.

Authors Chun-Heng Ho, Charles Eastman, and Richard Catrambone determined via their study that mathematical and spatial skills were unrelated, whereas performance on 2D and 3D spatial tasks consistently showed a correlation [46]; they emphasised design-instruction approaches that enable efficient utilisation of 2D techniques when addressing 3D design challenges.

The researchers in an American study [47] employed the PSVT:R [33] and the SBST [6] to conclude that diverse techniques are utilised to tackle cross-section and rotation tasks, encompassing methods such as elimination, cognitive processes, reasoning, instinct, and guiding principles. The results provide valuable insights for creating strategies to enhance students' spatial skills.

George Bodner and Roland Guay, in 1997, developed the Purdue Visualisation of Rotations (ROT/PSVT:R) test, an assessment that minimizes analytical processing, and suggested it to be an apt predictor of students' difficulty with spatial tasks, especially in the domain of chemistry, with a verdict that there is a connection between students' success in beginner chemistry lessons and their spatial skills [33]. Another 2022 based research formulated the Santa Barbara Sense of Direction Scale (SBSOD) to assess the environmental spatial ability which exhibited good consistency and reliability. Results were strongly associated with performance on tasks involving orienting oneself in the environment, rather than estimating distances or drawing maps, with spatial knowledge gained from direct experience in the environment in comparison to other measures [45].

In the study of gender differences, the results of an early study conducted in 1987 by Stanley Coren and Clare Porac emphasized the significance of incorporating spatial cognitive abilities whilst examining visual illusions and indicated that certain aspects of spatial cognition may play a role in specific illusory distortions; they additionally found sex-related differences in spatial abilities [48]. According to an American study, males have superior verbal and spatial working memory abilities compared to women, which might account for gender inequalities in engagement in science [49]. The authors recommended examining the brain region and neurological correlates of various cognitive functions. Enhanced cognitive function, brain volume, and structural attributes of the white matter like fractional anisotropy are all positively associated with family socioeconomic status [10], as determined by a Japanese study in 2018. All these studies employed a wide range of assessment tools to measure spatial cognitive abilities, including psychological assessments and behavioural data analysis.

Studies in the domain of Architecture and Design considering the parameters of gender and other demographic factors was carried out in three research articles. In 1980, Sarah Burnett and David Lane found that college-level coursework in mathematics and physical sciences can enhance spatial ability, with students majoring in these subjects showing significant improvement compared to those majoring in social and humanistic sciences [50]. Another study presents the results of using the 3D Ability Test (3DAT) [51] to test freshmen students of design, which indicated statistically significant disparities in spatial performance between men and women, with men outperforming the women [52], and emphasized the significance of spatial ability in design education as a predictor of success in graphics-oriented modules. Ji Young Cho, a South Korea-based scholar, examined the academic performance of design freshmen in terms of innovation, spatial ability, and visual cognitive approach via the Torrance Test of Creative Thinking (TTCT), designed by Dr. E. Paul Torrance in 1966 and cited by [21], the Mental Rotations Test (MRT) [38], and the Architectural Spatial Ability Test (ASAT) [53], among other tests, and found no significant association; nevertheless, a positive association was observed between general spatial abilities and visual cognition. The study also highlighted the need to develop parameters for measurement of creativity and spatial ability that are domain-specific while emphasizing the necessity of having an in-depth understanding of students' potential and their academic development [21].

With digital intervention as a parameter, a study examined the relationship between various cognitive abilities through the Mental Rotations Test (MRT) [32] and the Santa Barbara Sense of Direction scale (SBSOD) [45] in addition to other assessments; small-scale spatial abilities were found to estimate performance on environmental-learning tasks, indicating that various spatial scales are somewhat but not completely distinct from one another. An exploratory factor analysis was carried out in order to obtain differences in environmental learning from firsthand exposure and instruction compared to learning from simulated environments and video content [54]. Another recent inquiry determined the effectiveness of an online spatial-skills training program via the Revised PSVT:R [33]. In the context of freshmen studying computer programming, the online program was noted to be effective at boosting spatial abilities, primarily for students identified as having a spatial-skills deficiency by a preliminary screening for spatial ability [55].

Angelica Moé, Chiara Meneghetti, and Mara Cadinu observed the impact of incremental theory in mental rotation tasks, a skill that is commonly associated with masculinity [56]. Female participants were tested with a virtual version of the Mental Rotations Test (MRT) [32]. Involvement and performance of women in mental rotations tasks can be driven by designed features, by aspects of mindset such as self-perception of competence, and by methods adopted [56].

An American study at the intersection of the domains of gender studies, developing of novel assessments, and in-depth inquiry into spatial–visual ability included an experiment that concluded with the finding of positive correlation between spatial aptitude and accuracy of 3D visualisation but not speed [20]. Employing a variety of standard evaluation tools, it determined that spatial ability can be utilised to compare comprehension mistakes and apprehend their causes, as the study related to visualisation comprehension.

One of the early American studies conducted solely in the field of interior design in 1987 determined that coursework can aid in improving perceptual ability, implying that subpar results on the Differential Aptitude Tests (DAT), which was designed to assess perceptual levels by Benett, Seashore, and Wesman in 1972, as cited by [57], should perhaps not hinder admission into the Interior Design program. As opposed to being a vital ability for the study of architecture, senior students' poor performance in comprehending abstract forms in architecture curricula, as observed from the outcomes of the American Educational Testing Services' Architectural Scholastic Aptitude Test (ASAT), is attributed to a lack of practise [58]. According to a study by Ji Young Cho, the computer-based Architectural Spatial Ability Test [53] and academic performance in architecture were linked, underlining the significance of spatial ability in academic achievements. Performance on that test nevertheless did not relate to performance on a variety of wider spatial skill tests or on the Torrance Test of Creative Thinking (TTCT), designed by Dr. E. Paul Torrance in 1966, as cited by [53]. In the context of architectural education, spatial awareness—involving an subconscious understanding of one's body in the world—is recommended as a supplement to established instructional approaches [59] and may assist learners in creating embodied experiences. Authors Ken Sutton, Anthony Williams, Danika Tremain, and Peter Kilgour concluded that the absence of a correlation between Australian Tertiary Admissions Rank (ATAR) and spatial performance, as evaluated by the 3D Ability Test (3DAT) [51] could have potential consequences for the current admission criteria for bachelor's-level architecture programs, thus necessitating an appraisal of spatial aptitude prior to enrolment at university [60]. The only Saudi Arabian study in which all participants were female [61] found that spatial aptitude is crucial for achieving academic success in the interior design program's early technical courses; however, it becomes an inadequate evaluation instrument during higher-level coursework.

With Architecture and Design curricula as the framework, many researchers have created instruments to evaluate the spatial–visual ability of potential candidates and students. Ken Sutton and Anthony Williams determined that the 3D Ability Test (3DAT) [51], which was devised to gauge spatial skills involved in technical drawings, was a credible indicator of spatial aptitude suitable for designers who had earlier demonstrated competence in technical drawing, positively correlating with better results on spatial ability tasks. The results implied the need to prioritise the perception of 2D–3D recognition for design-based courses. Beyond traditional psychometric approaches, the creation and validation of the Architecture and Interior Design Domain-Specific Spatial Ability Test (AISAT), a specialized spatial ability test for interior design and architecture, proposes significant benefits to academicians in the field of cognitive sciences [5]. For this study, participants completed two sets of spatial ability tests—General Spatial Ability (GSA), which had MRT [38] as a segment, and Domain-Specific Spatial Ability (DSA) (AISAT) [5]. Another study by the same scholars examined [22] the participants' design competence and compared it with their scores on a General Spatial Ability (GSA) test [5], along with their scores on a revised version of the Architecture and Interior Design Domain-Specific Spatial Ability Test (AISAT V.2) [22] and revealed that originality in spatial design, mental rotation, and spatial visualisation were all correlated to some degree.

Merely providing instruction in technical drawing is inadequate for the cultivation of cognitive visualisation capabilities; augmenting students' 3D spatial perception skills can be achieved by employing supplementary digital tools and instruments, as found by a Turkish study [62]. A very recent study observed that utilising head-mounted displays (HMD) to fully scale sketch architectural structures in virtual immersive settings can enhance spatial abilities [14], as assessed with MRT [32] among many other spatial ability tests.

Interactive graphics and simulated geometric solids were employed for the training of spatial visualisation, leading to a notable increase in the ability to identify and infer cross-sections of 3D objects [63], as assessed by the Santa Barbara Solids Test (SBST) [6].

Cheryl Cohen and Mary Hegarty found that the inability to change one's perspective and break convoluted solids down into basic geometric components are the two challenges that participants face while taking the spatial–visual ability tests, specifically the Mental Rotations Test (MRT) [32] and the Visualisation of Views Test (VV) designed by Roland Guay in 1976, as cited by [6]. They developed a novel assessment tool, the Santa Barbara Solids Test (SBST), based on these findings.

Table 7. Ages 18 years to 22 years—A5.

Reference	Country	Year	Age	Sector	Objective
[4]	USA	2018	University students	A	Evidence for the beneficial effects of spatial-skill development on potential STEM competence.—MRT
[5]	South Korea and USA	2021	18–30 years	C + E	Development and validation of the Architecture and Interior Design domain-based spatial ability Test (AISAT).—MRT, SVA 1 (2D to 3D), SVA 1A (2D to 3D), SVA 2 (3D to 2D)
[6]	USA	2007	University students	G	Examine the impact of altering the orientation of the cutting plans and the geometric structure on performance in spatial visualisation tasks and create a psychometric assessment tool to evaluate variations in an individual's ability to mentally visualize cross-sections of 3D objects.—MRT, SVA 2 (3D to 2D)
[9]	France	2021	University freshmen	A + B	Examine the implications of spatial visualisation abilities on academic achievement in the study of engineering.—MRT, SVA 1 (2D to 3D), SVA 2 (3D to 2D) (OB)
[10]	Japan	2018	MA = 20.7 years	B + I	Investigate the interplay between family SES and psychological evaluations to gain insight into the nature of family SES correlates.—NA
[14]	Spain and Peru	2021	First-year and final-year university students	C + D	Examine the progression of spatial cognition in relation to capturing spatial experiences in virtual immersive settings.—MRT, SVA 1 (2D to 3D), SVA 2 (3D to 2D)

Table 7. *Cont.*

Reference	Country	Year	Age	Sector	Objective
[20]	USA	2005	Graduate and undergraduate students	B + E + F	Explore the correlation between spatial aptitude and comprehension of visual representations.—NA
[21]	South Korea	2016	University freshmen	B + C	Examine the link among design studio outcomes and innovation, spatial aptitude, and visual cognition.—MRT, SVA 1 (2D to 3D), SVA 1A (2D to 3D), SVA 2 (3D to 2D)
[22]	USA	2020	University students	C + E	Investigation of the relationship between multifaced creativity and domain-based spatial skills in the context of 3D explorations within interior design.—MRT, SVA 1 (2D to 3D), SVA 1A (2D to 3D), SVA 2 (3D to 2D)
[33]	USA	1997	Undergraduate students	A + E	Examine the correlation between spatial aptitude and academic achievement in entry-level chemistry classes.—MRT, SVA 1 (2D to 3D) (OB)
[34]	USA	2013	University freshmen	A	Validation with evidence to support the use of Revised PSVT:R [37] in assessing spatial ability in association with other academic markers.—MRT, SVA 1 (2D to 3D), SVA 2 (3D to 2D) (OB)
[35]	USA	2014	University students	A	Evaluate the effect of a variety of drawing methods on the students' spatial visualisation abilities in engineering.—MRT
[36]	Turkey	2016	Second- and third-year university students	A	Examine the correlation between potential teachers' academic success and spatial skills.—MRT, SVA 1 (2D to 3D)
[37]	Portugal	2022	University students	A	Assess pre- and post-GIS spatial-perception transitions. Explore gender's influence on engineering education's STAT test.—NA
[38]	Canada	1995	Undergraduate students MA of males = 21.3 years MA of females = 20.5 years	A + B	Inspect the MRT in comparison to the Card-Rotations Test and the Paper-Folding Test.—MRT
[39]	USA	1998	University students MA = 21.7 years	A + B	Compare gender-based differences in performance on cognitive spatial assessments, particularly assessments of mental rotation competence and object location recall.—MRT
[40]	USA	2002	Undergraduate students	A + E	Develop a standardized self-report scale (SBSOD [45]) to assess environmental spatial skills.—NA
[41]	Austria and Germany	2005	University students	A + B	Assess the variance in achievement in descriptive geometry education between experienced and non-experienced cohorts.—SVA 2 (3D to 2D)
[42]	Hungary	2007	University students	A + B	Examine the outcomes of the MCT [46], placing emphasis on disparities in spatial acumen between genders.—SVA 2 (3D to 2D)
[43]	USA	2012	Undergraduate students	A + B	Creation and implementation of a novel assessment designed to gauge an individual's aptitude in recognizing the 2D cross-section of a 3D geometric solid.—MRT, SVA 2 (3D to 2D)
[44]	Sweden	2021	University students	A + B	Verification of gender differences in spatial competence via a spatial orientation assessment—Santa Barbara Sense of Direction Scale (SBSOD) [46].—NA

Table 7. *Cont.*

Reference	Country	Year	Age	Sector	Objective
[46]	USA	2006	Graduate and undergraduate students	A + C	Examine the efficacy and fluctuation of various depictions, encompassing spatial and mathematical ones.—MRT
[47]	USA	2019	First-year university students	A + G	Assess the techniques employed by students to solve problems in a class on spatial visualisation.—MRT, SVA 1 (2D to 3D) (OB)
[48]	Canada	1987	University students	B	Explore the correlation between variations in spatial cognitive skills and the size of visual illusions.—MRT, SVA 1 (2D to 3D) (OB)
[49]	USA	2005	University students	B	Examine the gender-based cognitive differences in performance regarding verbal and spatial working memory, and comprehension of material provided in both written and graphical formats.—MRT
[50]	USA	1980	First-year college students	B + C	Investigate whether spatial ability can be improved through university-level training.—MRT
[51]	Australia	2007	University graduate students	C + E	Verify a novel psychometric test devised to assess spatial abilities used in technical drawing and evaluate participant performance on activities involving spatial reasoning to identify 3D features from 2D drawings.—MRT, SVA 1 (2D to 3D), SVA 2 (3D to 2D) (OB)
[52]	Australia	2010	First-year university students	B + C	Explore the correlation between spatial aptitude and creative design skills among freshmen studying design.—MRT, SVA 1 (2D to 3D), SVA 2 (3D to 2D) (OB)
[53]	USA	2012	18 years	C	Establish correlations among spatial abilities, creativity, and proficiency in architectural design.—MRT, SVA 1 (2D to 3D), SVA 1A (2D to 3D), SVA 2 (3D to 2D) (OB)
[54]	USA	2006	MA = 22 years	B + D	Identification of the origins of variability in environmental spatial tasks and determination of whether performance in these tasks is indicative of a unified skill or a diverse range of skills.—MRT, SVA 1A (2D to 3D)
[55]	Canada	2021	First-year university students	B + D	Determine the efficacy of instruction in virtual spatial abilities offered to both genders in a CS1 program.—MRT, SVA 1 (2D to 3D) (OB)
[56]	Italy	2009	MA = 21.24 years	B + H	Examine the impact of incremental theory on women's performance in mental rotation tasks.—MRT
[57]	USA	1987	University graduate students	C	Examine the importance of the conventional assessments administered to incoming interior-design students.—SVA 1A (2D to 3D)
[58]	USA	2011	Undergraduate students	C	Examine spatial reasoning in architectural education, with an emphasis on the perception and cognition of primary shapes and their manipulation towards objectives.—MRT, SVA 1 (2D to 3D), SVA 1A (2D to 3D), SVA 2 (3D to 2D) (OB)

Table 7. *Cont.*

Reference	Country	Year	Age	Sector	Objective
[59]	Romania	2013	Second- and third-year university students	C	Cultivating spatial sensibility in architecture students is vital, especially in relation to the site's context and socio-cultural dimensions.—NA
[60]	Australia	2016	First-year university students	C	Examine the association between spatial cognition and the university admission rating (ATAR) of design students.—MRT, SVA 1 (2D to 3D, SVA 2 (3D to 2D) (OB)
[61]	Saudi Arabia	2019	First-year university students	C	Ascertain whether spatial aptitude influences achievement in the Interior Design program among female students.—MRT, SVA 1 (2D to 3D)
[62]	Turkey	2017	Second-year university students	C + D	Examine the methods employed by students to improve their technical drawing skills and the role of physical and digital models in enhancing this process.—NA
[63]	USA	2008	University students	D	Examine the merits of imparting spatial visualisations with interactive animations and virtual geometric solids.—SVA 2 (3D to 2D) (OB)

5.1.6. Ages 23 Years and above—Post-Graduate Students and Working Professionals (A6)

With 6 studies focusing on individuals from the ages of 23 and above (Table 8), ref. [64] found that despite the importance of spatial activities for STEM achievement, early childhood education prioritizes reading and numeracy above spatial activities and determined that educators' spatial anxiety has a notable impact on the utilisation of spatial activities in the classroom.

Table 8. Ages 23 years and above—A6.

Reference	Country	Year	Age	Sector	Objective
[3]	Turkey	2010	Student mathematics teachers	A + D	Ascertain the impact of geometrical assignments and tasks utilizing Google SketchUp on the spatial–visual ability of student mathematics instructors.—SVA 2 (3D to 2D) (OB)
[64]	Ireland	2023	Classroom teachers	A	Examine early childhood educators' formal and informal spatial activities with reading and math.—NA
[65]	USA	2006	Working professionals	E + G	Development of a concise survey to evaluate variations in the way individuals perceive and visualize objects and space.—NA
[66]	Australia	2003	MA = 26.32 years	F	Investigate the correlation between spatial aptitude and visual imagery via varied stimuli.—MRT, SVA 1 (2D to 3D), SVA 2 (3D to 2D) (OB)
[67]	USA	1971	Adults	G	Evaluate the time taken to identify the shape of a 3D object based on the difference in their orientations.—NA
[68]	USA	2003	Enlisted members of the US Air Force	J	Ascertain whether anything akin to spatial ability or temporal ability dominated performance on dynamic spatial-skills tasks.—NA

A Turkey-based study employed the Santa Barbara Solids Test (SBST) [6] and concluded that the spatial visualisation ability of student mathematics educators improved substantially when they utilised geometric tasks and assignments based on Google SketchUp [3].

The Object-Spatial Imagery Questionnaire (OSIQ) [65] was developed for the purpose of evaluating variations in inclinations towards and interactions with visual imagery and comprises two scales: one for visual depiction and another for spatial–visual representation, the former analysing choices for comprehending detailed and colourful pictures of individual objects and the latter focusing on choices for comprehending diagrams, spatial connections within objects and spatial alterations, with the OSIQ shown to possess predictive, bias, and ecologic reliability [65].

Employing a plethora of spatial ability tests, Lorelle J. Burton found that tests of spatial aptitude had a substantial correlation with visual imagery tasks that involved mental synthesis or transformation of visual shapes [66].

Scholars Roger Shepard and Jacqueline Metzler found that the time needed to choose between two perspective illustrations that depict identical 3D items is (i) an outcome of the angle variation between the two items' depicted positions and (ii) not less for variations that related merely to a rigid rotation of either of the illustrations in its own picture plane than for variations that related to a rotation of the 3D item in depth [67].

The only study that included U.S. Air Force members as participants determined that the capacity to predict when a moving item will arrive at a location or to judge the timing of impact is known as dynamic spatial ability and that it has less to do with spatial processes and more to do with time [68].

5.1.7. Mixed Age Groups (A7)

Table 9 shows studies that took into account individuals from all age groups. Author Elliot M. Tucker-Drob established through the findings in his study that parental education correlates with age trends in a variety of cognitive and success areas through both domain-general and domain-specific routes, which implied that while socioeconomic disparities are mostly evident in worldwide aspects of cognitive development, they have progressive connections to certain kinds of academic accomplishments [11].

Table 9. Mixed age groups—A7.

Reference	Country	Year	Age	Sector	Objective
[11]	USA	2013	5 to 18 years	B	Evaluate the degree to which developmental pathways particular to a certain domain or generic to a domain may account for socioeconomic variations in age patterns in various kinds of cognition and success.—MRT (OB)
[12]	Switzerland	2020	University Graduate + Post Graduate students	B + C + E	Evaluate spatial ability tests with varying degrees of domain specificity to architecture while looking into variations in test performance between genders with consideration of general reasoning ability.—MRT, SVA 1 (2D to 3D), SVA 2 (3D to 2D)
[13]	South Korea	2019	21 to 25 years	B + C	Investigate the association between spatial ability details and interior-design performance with two sets of spatial ability-measuring instruments, AISAT [13] being one of them.—MRT, SVA 1 (2D to 3D), SVA 1A (2D to 3D), SVA 2 (3D to 2D)
[15]	Mexico	2019	19 to 38 years	D	Explore the correlation between visual–spatial aptitude and the acquisition of computer-graphics knowledge.—MRT, SVA 1 (2D to 3D (OB)

Table 9. *Cont.*

Reference	Country	Year	Age	Sector	Objective
[32]	USA	1978	Elementary school + High School + University students	E	Examine the development and reliability of the Mental Rotations Test in accordance with Shepard and Metzler's [67] stimulus.—MRT
[40]	Germany	2003	Group A = 15 years to adults Group B = 4 to 6 years	E	Establish and verify two novel assessments for measuring spatial ability.—MRT, SVA 2 (3D to 2D) (OB)
[69]	Germany	2005	10 to 20 years	B + D	Investigate the association between computer game choice and MRT performance with respect to gender differences with examining gender variations in both.—MRT
[70]	Germany	2010	Group A = 20 to 29 years Group B = 50 to 59 years	B + D	Assess the impact of age and gender on mental rotation and spatial comprehension derived from virtual environments.—MRT
[71]	Italy	2009	15 to 22 years	B + H	Examine a theoretical rationale for the disparities in gender identified during the administration of the Mental Rotation Test [32].—MRT
[72]	Taiwan	2015	18 to 25 years	C	Investigate how comprehension of spatial relations, spatial orientation, and spatial–visualisation impact the proficiency of designers in 3D product design.—SVA 1 (2D to 3D)
[73]	USA	2023	Mixed Age Groups	E	Build on prior models of spatial ability and tactics to shed light on BLV spatial strategies.—SVA 2 (3D to 2D)
[74]	USA	2012	Junior High + High School + University students	E + F	Establish the fundamental elements of spatial thinking by means of factor analysis and verification of the spatial-thinking ability test (STAT) [74].—MRT, SVA 1 (2D to 3D)
[75]	USA	2007	19 to 64 years	E + G	Establish the Everyday Spatial Behavioural Questionnaire (ESBQ), a tool to gauge several behaviour patterns wherein subjects describe the employment of various aspects of spatial intelligence.—MRT, SVA 1 (2D to 3D)
[76]	Portugal	2004	MA A = 19.22 years MA B = 21.47 years	F	Examine the spatial literature, evaluating multiple assessments, and empirically investigate and validate the spatial domain's dimensionality.—MRT, SVA 1 (2D to 3D), SVA 2 (3D to 2D) (OB)
[77]	Austria + Germany	2003	MA A = 17.7 years MA B = 46.1 years	G	Justify the significance of individual variations in technique implementation in both study and evaluation.—MRT, SVA 1 (2D to 3D), SVA 2 (3D to 2D)

A South Korea- and USA-based study by Ji Young Cho and Joori Suh revealed that 2D-to-3D visualisation skill, as measured via the Architecture and Interior Design Domain-Specific Spatial Ability Test (AISAT) [13] corresponded with the resultant object's distinct characteristics and multi-dimensional constitution. While the performance of men exceeded that of women in general spatial ability, women outperformed men in the area of design, which emphasised the significance of developing 2D-to-3D visualisation ability in interior-design curricula to enhance creative outcomes [13].

Two separate German studies conducted 5 years apart both found that males outperformed women in mental rotation. Claudia Quaiser-Pohl, Christian Geiser, and Wolfgang

Lehmann examined the link between preferences for online gaming, sex, and mental rotation ability; this study revealed gender disparities in the distribution of player categories, with notably more women in both the logic-and-skill gaming and non-player categories and increasingly large numbers of men in the action-and-simulation gaming category [69]. With a common author between these studies (the second being authored by Wolfgang Lehmann, Robby Schoenfeld, and Bernd Leplow), they studied the impact of gender and age on mental rotation and spatial perception from simulated realities and determined that senior citizens and women tend to have less familiarity with online games, which can impair their ability to use interfaces such as joysticks [70].

Angelica Moe, in her research based on incremental theory and performance of women, suggested that cognitive performance can be influenced by beliefs about one's talents [71]. Females improve in the Mental Rotation Test [32] when they are told they do better than males. They benefited from an intervention encouraging the expectation of success by promoting the idea of in-group capabilities in the provided task. On the contrary, men appeared to be more influenced by directions related to aspects of the task, with their scores improving when they believed the task to be easier, and they considered themselves to be more able than women [71].

A Switzerland-based study in 2021 created three new assessment tests to measure the spatial cognitive functions that are typically required in architectural studies: the Urban Layout Test (ULT), the Indoor Perspective Test (IPT), and Packing [12]. These assessments are domain-specific and responsive to spatial skills that are acquired through architectural education. The study also found that spatial abilities evolve during architectural education, with improvement demonstrated at the outset of the career path. The findings indicated that with more experience, both genders scored better on spatial tests with men consistently outscoring women, which indicated the requirement for more training. In order to gain an in-depth comprehension of architecture-specific spatial cognition, the study also emphasised the need to conduct additional research on domain-specific spatial abilities in architecture, especially among professionals [12].

Kun-Hsi Liao explored the connections between different spatial abilities (relations, orientation and visualisation) and designers' performance in 3D carton box design [72], stressing the vital role of spatial abilities in the field of product design.

A Mexican inquiry in 2019 provided empirical verification that a computerised graphics (CG) course like those often offered in STEM programmes can facilitate the growth of proficient visual–spatial skills [15].

Steven Vandenberg and Allan Kuse developed the Mental Rotations Test [32], which is extensively employed by researchers worldwide. This paper-and-pencil test to evaluate spatial–visualisation, created using Shepard and Metzler's stimuli [67]; demonstrated significant reliability across tests, internal uniformity, and consistent gender disparities among several demographics [32]. Claudia Quaiser-Pohl presents two novel assessment tools in a 2003 German- based study: the Mental Cutting Test ”Schnitte” developed by Fay & Quaiser-Pohl, as cited by [40], and the Picture Rotation Test [40]. Complex modifications of spatially displayed information constitute the basis of tests of abilities in spatial visualisation. To identify the resulting 2D cut surfaces, respondents mentally cut 3D void volumes with planes of other figures in the “Schnitte” Mental Cutting test, which was particularly designed to test individuals for extraordinary spatial abilities. By contrast, the Picture Rotation test is similar to the renowned adult Mental Rotations Test (MRT [32]), with similar stimulus constructs [67] but for pre-primary and primary school children [40]. A very recent study in 2023 employed a “Tactile Mental Cutting Test” (TMCT), discussed in depth by Goodridge et. al, as cited by [73], in order to evaluate the spatial aptitude of individuals who are blind or have impaired vision. This instrument, TMCT, is an adapted version of the Mental Cutting Test (MCT).

The Spatial Thinking Ability Test (STAT) [74] consists of questions formulated based on the spatial components of spatial thinking established by earlier research and on spatial ideas; it only partially corresponded with the spatial components identified through factor analysis.

Scholars John Eliot and Mark Czarnolewski developed the Everyday Spatial Behavioural Questionnaire (ESBQ), which consists of 12 categories with 116 questions related to spatial behaviour. It offers a more thorough evaluation of spatial intelligence than do current tools, which merely gauge certain aspects of spatial abilities. The validity of the ESBQ was further supported by the study's finding of potent partial correlations between a number of spatial tests and ESBQ subscales [75].

The results of a Portuguese research inquiry into the basis of organisation and evaluation of spatial skills in the Portuguese population through confirmatory factor analysis suggested the importance of considering a spatial domain rather than a single spatial ability; the authors also observed that the spatial domain comprises various dimensions [76].

Authors Judith Gluck and Sylvia Fitting examined data on variations in intra- and interindividual strategies in mental rotation, spatial orientation, and navigation, with assessments of spatial competence. They emphasised conducting studies on spatial aptitude that include elements of strategy, since everyone tackles spatial problems alternatively [77].

5.1.8. Age—Not Applicable (A8)

As shown in Table 10, the Purdue Spatial Visualisation Test—Visualisation of Rotations (PSVT:R) [33] has oversights in its isometric representations, despite the fact that isometric drawings are frequently utilized in spatial cognitive assessments for engineering and technology students [78]. Author Jianping Yue suggests that 3D solid modelling and modern computing technology may compensate for these errors and provide more accurate views in such tests [78]. A conference proceeding [79] examined the significance of cognitive spatial skills across various STEM fields and provides a synopsis of evaluation techniques for measuring cognitive spatial capability, particularly among engineering students. The techniques utilized encompass spatial tasks such as speed of closure, mental rotation in 2D and 3D, environmental scanning, etc. [79].

One of the earliest studies, which was conducted in 1985 by Marcia Linn, found that meta-analysis is beneficial for combining factual research and enables researchers to reach more reliable conclusions in comparison to other approaches [19]. The authors determined that gender disparities in spatial cognition vary in degree and are evident in specific traits; mental rotation exhibits substantial gender variations, though spatial perception exhibits fewer differences, with those differences being noticeable throughout life [19]. The work of Michael Peters and Christian Battista presents a concise overview of the 3D cube illustrations utilized by Shepard and Metzler [67] and its relevance to studies pertaining to psychological cognition and investigation of spatial behaviour [80]. In tasks comprising several figures, notably the Vandenberg and Kuse [32] test, the numbers show substantial gender disparities, whereas tests using paired display of identical 3D figures indicate minimal gender disparities [80].

Yukiko Maeda and So Yoon Yoon carried out a meta-analysis in 2012 that confirmed a significant gender disparity in mental rotation ability, with male subjects demonstrating greater proficiency on the PSVT:R [33] compared to their female counterparts [81].

The landmark study in 1979 by Mark McGee provided robust evidence via factor analysis supporting the presence of two distinct abilities in spatial cognition—visualisation and orientation. These abilities, which are more associated with success in technological, employment, and professional fields than verbal skills, lead to the accompanying effect of gender disparities in perceptual-cognitive functioning, which emerge during puberty and are influenced by genetic factors and hemisphere specialisation [1].

An American study in 2003 introduced a novel method by which to measure spatial aptitude and human spatial orientation with the utilisation of virtual reality (VR) and virtual environments (VE) by exploring their benefits as compared to conventional assessment methods [82].

Table 10. Not Applicable—A8.

Reference	Country	Year	Age	Sector	Objective
[1]	USA	1979	NA	B + I	Comprehensive psychometric investigations on human spatial skills, emphasizing on vision and orientation.—NA
[2]	India	2018	NA	F	Examine spatial-skill frameworks, concepts, and experimental studies to better comprehend this area of cognition.—NA
[19]	Israel + USA	1985	NA	B	Quantify sex disparities in spatial ability, establish their sources and determine the time of their appearance in a lifetime.—NA
[78]	USA	2006	NA	A	Discuss the relevance of isometric views in spatial–visualisation assessments, specifically in the PSVT:R [33].—MRT
[79]	USA	2012	NA	A	Summarize tests used to assess cognitive spatial ability in engineering students and evaluate the cognitive skills they look at.—NA
[80]	Canada	2007	NA	B	Provide both figures with stimuli on white and grey backdrops to address background choice.—MRT
[81]	USA	2013	NA	B + H	Estimate the gender difference in 3D mental rotation ability measured by PSVT:R [33] and examine the effects of testing conditions on differential performance by gender.—MRT, SVA 1 (2D to 3D) (OB)
[82]	USA	2003	NA	D	Discuss the advantages and limitations of Virtual Reality (VR) over conventional spatial ability assessments.—NA
[83]	USA	2003	NA	F	Present the premise of functional groupings of spatial skills as an organisational structure for scientific inquiry.—NA
[84]	USA	2008	NA	F	Investigate the way information processing mechanisms affect spatial abilities and study the gender inequalities via developmental research.—NA
[85]	Netherlands	2023	NA	F	Investigate the link between spatial skills and STEM problem-solving. Explore formal and informal spatial education methods to improve spatial skills. Examine gender and socio-economic status impacts on STEM and spatial aptitude.—NA
[86]	USA	1993	NA	G	Analyse and discuss the connection between G—general intelligence and spatial abilities.—MRT, SVA 1 (2D to 3D)
[87]	Europe + USA	2008	NA	J	Assess the efficacy of instruments employed to gauge the 3D spatial skills of engineering students.—MRT, SVA 1 (2D to 3D), SVA 2 (3D to 2D) (OB)

The comprehension of the psychometric associations of environmental learning discusses the framework that underlies human spatial cognition [83], and the concept of functional classifications of spatial skills is put forward for structuring spatial research and steer empirical investigations in the article authored by Gary Allen. Another review of spatial cognition by James Mohler provides a chronological survey of spatial skill studies, comprising key psychological and other literature [84]. Mohammed Tanweer validates the significance of information processing in spatial ability and the establishes theoretical models to define it, with psychometric studies examining spatial ability, developmental studies tracking its age-related progression, differential studies revealing gender-based differences, and information-processing literature exploring individual strategies and processing [2]. Ref. [85] provides extensive insights on the need for spatial interventions in practical educational settings to understand the connection between spatial abilities to STEM learning. Complex STEM challenges improve students' spatial abilities and cross-disciplinary subject understanding which implicates that research and education must embed both integrated as well as informal STEM training as effective methods for enhancing the spatial abilities of students.

Traditionally perceived as practical and mechanical aptitudes, spatial abilities are now acknowledged for their significance in abstract reasoning and creative thought. Spatial tests serve as assessments for general intelligence—G, gauging both overall cognitive abilities and task-specific skills, while also correlating with performance in various other spatial tasks [86].

Based on the extensive documentation by Renata Gorska and Sheryl Sorby, diverse assessment tools have been employed to assess the spatial aptitude of engineering students across different audiences in Europe and the United States. When choosing a tool for educational research focused on the enhancement of spatial skills, it is crucial to have a clear understanding of the specific aspects that need evaluation [87] and the most commonly utilized assessments for gauging spatial cognition of engineering students globally are the MRT [32] and the MCT [40].

6. Discussion

Though studies of spatial–visual ability are extensive, research conducted on children below the age of 5 years is scarce, composing only 2.29% of all included studies; however, critical development of the cognitive abilities takes place in this developmental state. Both studies, as mentioned, emphasise the mental rotation aspect of the ability, as that is the only construct applicable within the age bracket of children until the age of 5 years. There is tremendous scope for developing assessments and techniques for evaluation as well as enhancement of spatial–visualisation ability in children.

It is evident that spatial training has a greater impact on younger children (6 years to 8 years old), but there is a dearth of research focused on this specific group, with relevant papers constituting 3.44% of all studies included; this research gap prevents researchers from accurately tracking development or assessing the effectiveness of interventions.

With barely 5.74% of the research concentrating on school-aged children and teenagers (9 years to 15 years old), a sizeable research gap within this age bracket is apparent. The studies here concentrate on assessing and enhancing the spatial–visual ability of school-aged children and understanding the impact of external influences on their cognition.

A variety of sectors are covered in the limited studies conducted on teenagers (16 years to 17 years old). At 4.59% of the total studies, they covered the correlates of performance in spatial ability, refinements of existing evaluation techniques to better assess the spatial cognition of learners, novel assessment tools, and digitally enabled methods to improve learners' spatial–visualisation abilities.

The inquiry into spatial skills has been most prominent in the technical fields of engineering, science, mathematics, etc., in which researchers aim to understand its relationship with social and economic factors, among other factors of demography. The differences between genders in spatial cognition, wherein men outperform women, appear to be maintained across every age range and testing modality. At 44.81% of all studies included, most of the studies involve individuals ranging from 18 years to 22 years old. Within this age bracket, most of the studies are in the fields of STEM, geometry, geography, architecture, interior design, product design, and design, stipulating the significance of spatial–visual ability as a vital capacity for these technical and design domains. Another quarter of the research is dedicated to understanding the ramifications of social and economic status on spatial cognition, developing evaluation criteria, and developing training strategies supported by those criteria. Utilisation of digital tools has become a norm for the enhancement as well as the measurement of spatial visualisation ability.

Historically, spatial–visual ability was regarded as a crucial skill in the selection of candidates for professions requiring mechanical aptitude and technical competence. In the vast domain of spatial cognition, a wide array of categories has been identified, with a variety of assessment measures developed for each category. Among the vast array of techniques established over the years to assess spatial–visual ability, apart from the

Architecture and Interior Design Domain-Specific Spatial Ability Test (AISAT V.2) [22], none of the other tests encompass all the required subconstructs specific to architecture and interior design.

The number of studies falls drastically to 6.89% once the individuals complete formal education and enter professional life (23 years old and above). As their career path is defined, their performance in their professions is measured against their academic achievements to comprehend the influences on their spatial cognition. Many studies focus on the selection of spatial strategies to resolve space-related tasks.

A total of 17.23% of research does not take specific age groups into account. Nearly a quarter of the studies in the mixed-age group focus on establishing novel tools for the assessment of spatial cognition in the domains of architecture and interior design. Another major segment focuses on identifying the impact of external social, economic and educational forces on the spatial–visual ability of individuals. Substantial research has corroborated that computerised/online and other multimedia approaches like gaming, etc. can cultivate visual–spatial skills. Consistent investigations have also been carried out to elucidate the constructs of spatial skills and the schema employed for spatial competence.

Within the 14.93% of the inquiry that does not consider participants' age as a parameter, a significant section of the research discussed the underlying framework of spatial cognition, providing a conceptual structure in which to determine its subconstructs within the typology of inquiry. Studies confirmed that spatial skills are an indication of general intelligence, much beyond the conventional notion of them as a mechanical aptitude. Gender disparities in spatial skill assessments have been consistently apparent over time, as also suggested here.

7. Limitations and Future Research

The universality of insights from this overview of spatial–visual abilities is contingent upon the distinctive nature of the inquiry and the range of the literature under scrutiny, which may limit its relevance to diverse contexts or groups. Owing to constraints in time, resources, and information, this study might not include all pertinent literature. A potential predisposition in favour of published studies could result in the exclusion of significant unpublished papers or research undertaken in languages other than the ones that were reviewed.

As evidenced in this study, there is a compelling need to identify tactics to develop the spatial skills of children, beginning in the formative years. Education materials like textbooks, etc., can balance text and diagrams for better comprehension leading to enhancement of cognition. Innovative teaching strategies like video games, interactive animations, etc. can be employed to attract the younger population.

8. Implications of the Study

The exclusion of sources such as newspaper articles, magazines, books, website content, blog posts, etc. was primarily justified by the study's scope, which sought to compile the most recent and relevant research findings from peer-reviewed journals and scholarly publications. Although these sources likely offered valuable insights, their omission was imperative in order to maintain the review's relevance and precision with regard to the research inquiry. By covering literature spanning several decades, this study is able to broadly touch upon the historical development of the concepts of cognitive abilities, the investigation of underlying subconstructs, methodologies, and assessment techniques pertinent to the domain of spatial–visual abilities. This overview is multi-disciplinary, including literature from various disciplines in order to ensure a thorough comprehension of spatial skills.

Among the many implications of this study, first and foremost is the contribution to knowledge of spatial skills across diverse domains. It also identifies cognitive skills needed for academic and vocational success. This inquiry sheds light on the gender disparities apparent in most of research articles examined, which call for more training of spatial abilities in various sectors. To address the gender gap, the design of the instruction material should focus on tasks that re particularly beneficial to female students. Many of the spatial skills assessments discussed in this paper can be utilized as a framework to develop novel and domain-specific evaluation instruments. Several CAD, virtual reality (VR), and augmented reality (AR)-based strategies are discussed that can improve spatial abilities in problem-solving scenarios, especially for STEM-related outcomes. Additionally, this inquiry also provides a framework for understanding spatial abilities in architecture and interior design.

9. Conclusions

The integration of strategic approaches into conventional spatial tests is key to enhancing the assessment of spatial ability, offering deeper insights into individual differences and the impact of parental education on academic achievement. Research highlights a strong link between general intelligence and spatial thinking, underlining the importance of synthesizing new information and fostering intellectual creativity. This necessitates investigations into the role of spatial visualisation in university enrolment and professional development, particularly in fields like architecture and interior design. The Architecture and Interior Design Domain-Specific Spatial Ability Test (AISAT V.2) [22] is notable for its unique focus, helping educators assess and understand student proficiencies in spatial design and tailor their teaching methods accordingly. However, there is a need for more diverse and comprehensive assessments across different populations and cultures.

Recent studies have increasingly utilized digital tools such as virtual environments, immersive settings, and simulated realities to enhance spatial cognition, suggesting potential new educational strategies and instructional programs to improve spatial learning abilities. Three key areas require further exploration: (i) the link between spatial skills and design performance, (ii) the development of specialized tools for measuring spatial skills across various domains, and (iii) the use of virtual-reality technology in spatial-skills training. Additionally, recognizing the adaptability required in teaching methods for spatial-based learning opens new avenues for research in design thinking and reasoning.

Most research in this field has been conducted in nations with advanced economies, especially the USA, with varied applications across different sectors. This highlights a significant gap in research from emerging and developing economies in Asia and Africa, pointing to the need for a global perspective on spatial abilities. Overall, this field demands a multifaceted approach that includes technological innovation, educational reform, and cross-cultural research, aiming to enhance the understanding and application of spatial skills worldwide.

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