

Spatial Learning Technologies for Inclusive Anatomy Education: A Systematic Literature Review of Virtual Reality, Augmented Reality, and Neurodiversity

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ABSTRAK

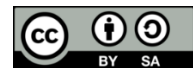
Pendidikan anatomi membutuhkan penalaran spasial tingkat lanjut dan semakin banyak menggunakan teknologi seperti realitas virtual (VR), realitas tertambah (AR), Anatomage, dan pencetakan 3D. Perbedaan dalam pemrosesan visuospasial dan fungsi eksekutif di antara peserta didik dengan gangguan perhatian/hiperaktivitas (ADHD) menjadikan relevansi teknologi spasial untuk pendidikan inklusif sebagai area investigasi yang penting. Tujuan. Studi ini mensintesis bukti tentang efektivitas modalitas pembelajaran anatomi spasial digital dan implikasinya bagi peserta didik neurodivergen, khususnya mereka yang memiliki ADHD. Metode. Tinjauan literatur sistematis mengikuti PRISMA 2020 dilakukan pada publikasi dari tahun 2021 hingga 2026. Studi diidentifikasi di berbagai basis data, dipilih menggunakan kerangka kerja PICOS, dinilai menggunakan Mixed Methods Appraisal Tool dan AMSTAR-2, dan disintesis secara naratif dan tematik. Hasil. Dua puluh enam studi dikelompokkan menjadi lima kluster tematik. Modalitas 3D digital umumnya sebanding atau lebih unggul daripada metode konvensional dalam meningkatkan pengetahuan faktual dan spasial, dengan efektivitas yang dipengaruhi oleh kemampuan visuospasial awal peserta didik. Literatur tentang ADHD menunjukkan perbedaan dalam pemrosesan visuospasial, sementara AR dan VR dapat mengurangi beban kognitif dan meningkatkan keterlibatan. Namun, belum ada penelitian yang secara langsung meneliti teknologi anatomi spasial di kalangan mahasiswa kedokteran dengan ADHD. Kesimpulan. Terdapat kesenjangan bukti yang signifikan pada persimpangan neurodiversitas dan pembelajaran anatomi spasial, yang menyoroti perlunya penelitian empiris untuk mendukung pendidikan anatomi yang lebih inklusif.

ABSTRACT

Anatomy education requires advanced spatial reasoning and increasingly incorporates technologies such as virtual reality (VR), augmented reality (AR), Anatomage, and 3D printing. Differences in visuospatial processing and executive functioning among learners with attention-deficit/hyperactivity disorder (ADHD) make the relevance of spatial technologies to inclusive education an important area of investigation. Objective. This study synthesizes evidence on the effectiveness of digital spatial anatomy learning modalities and their implications for neurodivergent learners, particularly those with ADHD. Methods. A systematic literature review following PRISMA 2020 was conducted on publications from 2021 to 2026. Studies

were identified across multiple databases, selected using the PICOS framework, appraised using the Mixed Methods Appraisal Tool and AMSTAR-2, and synthesized narratively and thematically. Results. Twenty-six studies were grouped into five thematic clusters. Digital 3D modalities were generally comparable or superior to conventional methods in improving factual and spatial knowledge, with effectiveness influenced by learners' initial visuospatial ability. ADHD literature indicates differences in visuospatial processing, while AR and VR may reduce cognitive load and enhance engagement. However, no studies directly examined spatial anatomy technologies among medical students with ADHD. Conclusion. A significant evidence gap exists at the intersection of neurodiversity and spatial anatomy learning, highlighting the need for empirical research to support more inclusive anatomy education.

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1. INTRODUCTION

Anatomy is a fundamental component of medical education and inherently requires advanced spatial reasoning, including the ability to represent, mentally manipulate, rotate, and integrate three-dimensional structures from two-dimensional representations and physical objects. A meta-analysis by (Roach et al., 2021), involving 15 studies and 1,245 participants, confirmed a positive, although modest, correlation between spatial ability and anatomy performance ($r = 0.240$; 95% CI: 0.09–0.38), with stronger associations observed in practical and spatial relationship-based assessments than in non-spatial multiple-choice examinations. These findings suggest that students with lower spatial ability may be disadvantaged when curriculum delivery and assessment methods are not sufficiently adapted to differences in spatial reasoning. Evidence from Indonesia reinforces this concern. (Sarilita et al., 2022) reported moderate levels of spatial ability among dental students at Universitas Padjadjaran, accompanied by significant differences across gender and student cohorts. Collectively, these findings indicate that spatial ability represents an important learner characteristic in anatomy education and may influence how effectively students process complex anatomical structures, particularly when learning activities require the interpretation of spatial relationships and the mental transformation of anatomical representations.

For centuries, cadaveric dissection has been regarded as the gold standard in anatomy education because it provides authentic tactile experiences and facilitates an understanding of complex spatial relationships within the human body. A survey of anatomy faculty members confirmed that cadaveric learning offers important advantages, including exposure to real anatomical variation and opportunities to develop professionalism and ethical awareness, dimensions that remain difficult to fully replicate through digital media (Asad et al., 2023). However, ethical, logistical, financial, and accessibility constraints, together with the limited availability of cadavers, have accelerated the development and adoption of alternative spatial learning modalities. These include virtual reality (VR), augmented reality (AR), virtual dissection tables such as Anatomage, three-dimensional anatomy software, and 3D-printed anatomical models. Unlike conventional two-dimensional instructional resources, these technologies enable learners to interact

with, manipulate, and repeatedly explore three-dimensional anatomical structures. Their growing adoption therefore represents more than a technological transition from conventional to digital instruction. The educational value of these modalities may depend substantially on the interaction between technological features and learner characteristics, particularly the cognitive abilities required to process, retain, and manipulate spatial information. Understanding this interaction has consequently become increasingly important for designing effective and inclusive anatomy learning environments.

The importance of learner diversity becomes particularly evident when anatomy education is considered through the perspective of neurodiversity. The neurodiversity paradigm conceptualizes conditions such as attention-deficit/hyperactivity disorder (ADHD) not solely as deficits but as forms of neurocognitive variation that may present both challenges and strengths depending on the characteristics of the learning environment (Bailey et al., 2023). ADHD is characterized by persistent differences in attention, impulsivity, and activity regulation and is frequently associated with challenges related to executive functioning and working memory. Its relevance to medical education has received increasing attention, with a recent systematic review reporting that a substantial proportion of medical students experience meaningful symptoms of inattention while institutional support and accommodations for these learners remain insufficiently standardized (Lee & Zhang, 2025). This situation raises important questions regarding the extent to which existing educational environments adequately accommodate diverse cognitive profiles. In anatomy education, these concerns are particularly relevant because conventional learning frequently requires sustained attention, intensive working-memory processing, and the internal mental transformation of complex spatial structures. Consequently, the selection and design of anatomy learning modalities should not be evaluated solely according to their average effectiveness but also according to their capacity to accommodate differences among learners. From this perspective, the relationship between learning technologies and neurocognitive diversity represents not only a pedagogical issue but also an important dimension of educational equity and inclusive education.

There is a theoretical basis for proposing that spatial anatomy learning modalities may interact with cognitive characteristics associated with ADHD. A systematic review by (Nejati et al., 2024) reported that individuals with ADHD may demonstrate slower visuospatial processing and weaknesses in visuoconstructive abilities. Importantly, however, this pattern is nuanced, as evidence for a specific deficit in mental rotation remains inconsistent. ADHD should therefore not be characterized as a generalized spatial deficit but rather as a condition associated with differences in particular aspects of visuospatial processing and executive functions that support complex cognitive tasks. These characteristics are particularly relevant to anatomy education because visual memory and spatial intelligence have been associated with academic achievement in anatomy courses (Aspanani et al., 2023), directly linking visuospatial cognitive processes with anatomy learning outcomes. From the perspectives of cognitive load theory and multimedia learning, externally represented and manipulable three-dimensional objects may reduce the cognitive demands associated with internally transforming spatial information. Such representations may facilitate cognitive offloading by shifting part of the spatial transformation process from learners' working memory to the external learning environment. This mechanism may be particularly relevant for learners whose visuospatial working-memory capacity or executive functioning becomes more vulnerable under cognitively demanding learning conditions.

Recent empirical evidence outside the context of anatomy provides preliminary support for the potential of immersive and interactive technologies to address some of these challenges. Spatial AR combined with generative artificial intelligence scaffolding has been reported to enhance task salience and reduce perceived cognitive load among university students with ADHD (Parmar et al., 2026). Similarly, the integration of VR with electroencephalography (EEG) has enabled the neurophysiological assessment of attention and cognitive load among university students with ADHD (Wolfers et al., 2026). These findings suggest that immersive and interactive technologies may

have the potential to support attention, engagement, and cognitive processing among neurodivergent learners by providing more interactive, visually salient, and externally structured learning environments. Nevertheless, whether these potential benefits extend specifically to spatial anatomy education remains unknown. This uncertainty is particularly important because immersive technologies are not inherently beneficial for all learners or learning situations. Their effectiveness may depend on instructional design, the alignment between technology and learning objectives, learners' prior spatial ability, and the cognitive demands imposed by the learning environment. Therefore, examining the implications of spatial technologies for neurodivergent learners requires a synthesis that extends beyond simple comparisons of technological effectiveness.

Two bodies of literature have consequently developed largely in parallel. The first examines the effectiveness of digital spatial learning modalities, including VR, AR, Anatomage, and 3D printing, in anatomy education, often in comparison with cadaveric dissection or conventional instructional approaches. The second investigates the cognitive characteristics, educational experiences, and accommodation needs of learners with ADHD and other forms of neurodiversity. Despite their conceptual relevance to one another, these bodies of research have rarely been integrated within the context of anatomy education. This gap is important because spatial ability may influence how learners benefit from technology-enhanced anatomy education, while ADHD is associated with differences in cognitive processes relevant to spatial learning, working memory, attention, and executive functioning. Accordingly, this systematic literature review addresses the following research question: Among medical students, how effective are digital spatial anatomy learning modalities, including virtual reality, augmented reality, Anatomage, and 3D printing, compared with cadaveric dissection or conventional teaching methods in improving knowledge and spatial learning outcomes, and to what extent does the existing evidence consider neurodivergent learners, particularly those with ADHD? This review aims to synthesize evidence regarding the comparative effectiveness of digital spatial learning modalities and cadaver-based or conventional approaches in anatomy education, examine the role of spatial ability as a predictor and potential moderator of anatomy learning outcomes, review cognitive characteristics associated with ADHD that are relevant to spatial learning, identify evidence regarding the use of immersive and interactive technologies to support learners with ADHD, and identify knowledge gaps and future research directions at the intersection of neurodiversity and spatial anatomy education. By integrating these bodies of evidence, this review seeks to move beyond the question of whether digital technologies are effective in general and instead considers for whom, under what cognitive conditions, and through which mechanisms spatial learning technologies may contribute to more inclusive anatomy education.

2. RESEARCH METHODS

This study employed a systematic literature review following the Preferred Reporting Items for Systematic Reviews and Meta Analyses (PRISMA) 2020 guidelines (Page et al., 2021). Given the heterogeneity of study designs and the interdisciplinary nature of the research question, the evidence was synthesized using a narrative thematic approach rather than a quantitative meta analysis. Protocol registration in PROSPERO is recommended before the final execution of the search to enhance transparency and reduce the potential for duplication.

Study eligibility was determined using the PICOS framework. The population included undergraduate medical and biomedical students, with particular attention given to neurodivergent subgroups, especially individuals with attention deficit/hyperactivity disorder (ADHD), when such evidence was available. The interventions comprised digital spatial anatomy learning modalities, including immersive and desktop virtual reality (VR), augmented reality (AR), Anatomage tables, three dimensional anatomy software, and three dimensional printed models. Comparators included cadaveric dissection, plastinated specimens, atlases or two dimensional images, and other conventional teaching methods. Outcomes included anatomy knowledge acquisition and retention,

including factual and spatial knowledge, assessment performance, spatial ability, cognitive load, attention and engagement, and learner perceptions. Eligible study designs included randomized controlled trials (RCTs), quasi experimental studies, comparative studies, cross sectional studies, systematic reviews and meta-analyses, and relevant qualitative studies.

The inclusion criteria were publications published between 2021 and 2026, written in English or Indonesian, available in full text, and relevant to spatial anatomy learning modalities and or ADHD related learning cognition. Studies published before 2021, opinion papers or editorials without empirical data or relevant references, conference abstracts without full text, and studies conducted outside anatomy or medical education contexts that could not reasonably inform the research question were excluded. Established theoretical frameworks, including cognitive load theory and multimedia learning theory, originated from publications outside the five year search window. These frameworks were therefore referenced selectively in the Introduction and Discussion as theoretical foundations but were not counted as included studies and were not incorporated into the evidence synthesis.

The literature search was conducted across PubMed/MEDLINE, Scopus, Wiley Online Library, including relevant journals such as *Anatomical Sciences Education* and *Medical Education*, ScienceDirect, ERIC, and IEEE Xplore. Google Scholar was used as a supplementary search engine, with the first 150 records screened based on relevance. National and open access journal portals, including Garuda and DOAJ, were also searched to identify relevant Indonesian literature. In addition, hand searching and citation snowballing from the reference lists of key reviews were undertaken to improve the comprehensiveness of the search.

The search strategy was developed using combinations of keywords representing the major conceptual domains of the research question. Terms were combined using Boolean operators AND and OR and truncation symbols where appropriate. Search strings were adapted to the syntax of each database, including the use of Medical Subject Headings (MeSH) in PubMed where applicable. The publication period was restricted to 2021 through 2026 across all databases. The search strategy incorporated terms related to the study population, digital spatial learning interventions, conventional comparators, learning outcomes and anatomy education contexts, as well as a second search layer specifically addressing neurodiversity and ADHD. The main search combined population, intervention, and outcome or context terms, whereas the ADHD focused search combined population, neurodiversity, and outcome or context terms.

Table 1. Search Strategy By Conceptual Domain And Boolean Operators

Conceptual Domain	Keywords and Boolean Operators
Population	("medical student*" OR "undergraduate medical" OR "health science student*")
Intervention: Digital Spatial Modalities	("virtual reality" OR "augmented reality" OR "extended reality" OR "mixed reality" OR "Anatamage" OR "virtual dissection table" OR "3D printing" OR "three dimensional printed" OR "Complete Anatomy" OR "3D visualization" OR "stereoscopic")
Comparator	("cadaver*" OR "cadaveric dissection" OR "plastinated" OR "traditional teaching" OR "2D image*")
Outcomes and Context	("anatomy education" OR "spatial ability" OR "visuospatial" OR "spatial learning" OR "learning outcome*" OR "knowledge retention" OR "cognitive load")
Neurodiversity: Second Search Layer	("ADHD" OR "attention deficit" OR "neurodivers*" OR "neurodivergen*")
Combined Search Example	Population AND Intervention AND (Outcomes and context) AND Filter [2021:2026]. The ADHD search was conducted as a second layer: Population AND Neurodiversity AND (Outcomes and context) AND Filter [2021:2026].

Records retrieved from the databases were exported to reference management software, and duplicate records were removed before screening. Study selection was conducted in two stages, beginning with title and abstract screening followed by full text assessment. Screening was performed independently by at least two reviewers. Disagreements were resolved through

discussion and, when necessary, consultation with a third reviewer. Structured data extraction included study identification, study design, population characteristics, learning modality and comparator, outcome instruments, key findings, and whether spatial ability or participants' neurodiversity status was considered in the study.

Because the included evidence consisted of multiple methodological approaches, study quality was assessed using instruments appropriate to each study design. The Mixed Methods Appraisal Tool (MMAT) 2018 was used for quantitative, qualitative, and mixed methods primary studies. AMSTAR 2 was used to assess systematic reviews and meta analyses, while the Cochrane Risk of Bias 2 tool was applied to randomized controlled trials. Quality assessment findings were used to inform the narrative weighting and interpretation of the evidence rather than serving as an automatic basis for study exclusion.

A narrative thematic synthesis was conducted by grouping findings into analytical themes aligned with the research question. This approach was selected because substantial heterogeneity in learning modalities, outcome measures, and study designs prevented a valid quantitative pooling of effect estimates. The thematic synthesis also enabled the integration of empirical evidence from anatomy and medical education with evidence concerning ADHD related neurocognitive characteristics and technology supported learning. The resulting synthesis was used to identify patterns in the effectiveness of digital spatial learning modalities, examine the role of learner spatial ability, assess the relevance of ADHD related cognitive characteristics, and identify evidence gaps at the intersection of neurodiversity and spatial anatomy education.

3. RESULTS AND DISCUSSION

3.1 Results

The identification, screening, and eligibility assessment processes are summarized in Figure 1. Of the 762 records initially identified, comprising 644 records retrieved from databases and 118 records obtained from other sources, 187 duplicates were removed. A total of 575 records were subsequently screened based on their titles and abstracts, while 98 reports were assessed for eligibility through full-text review. Of these, 72 reports were excluded, primarily because they involved populations other than medical or anatomy students ($n = 22$) or were published before 2021 ($n = 21$). Ultimately, 26 studies met the eligibility criteria and were included in the narrative and thematic synthesis.

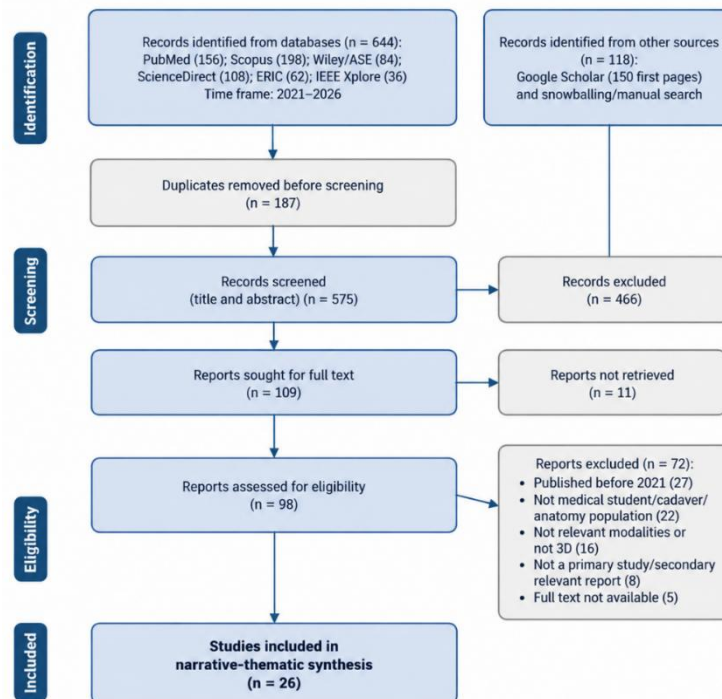


Figure 1. PRISMA 2020 Flow Diagram of the Study Selection Process

The characteristics of the 26 included studies are presented in Table 2 and organized into five thematic clusters: VR and AR modalities (6 studies), 3D printing (3 studies), Anatomage and cadaver-based learning (4 studies), spatial ability (7 studies), and ADHD and neurodiversity (6 studies). The evidence base was dominated by systematic reviews and meta-analyses, complemented by randomized controlled trials (RCTs), correlational studies, surveys, and intervention studies. All included studies were published between 2021 and 2026.

3.2 Characteristics of the Included Studies

Table 2. Characteristics of the included studies (n = 26; publication period: 2021–2026)

No.	Citation	Journal / Source	Study Design	Key Findings
1	(Salimi et al., 2024)	Anatomical Sciences Education, 17(6)	Systematic review and meta-analysis	VR/AR improved anatomy knowledge acquisition compared with traditional instructional methods; effectiveness was moderated by learners' visuospatial ability.
2	(García-Robles et al., 2024)*	Anatomical Sciences Education (PROSPERO CRD42023423017)	Systematic review and meta-analysis	Immersive VR (iVR) and AR produced meaningful improvements in knowledge acquisition, and most students perceived XR devices as useful for learning.
3	(Minouei et al., 2024)*	BMC Medical Education, 24, 1407	Systematic review using the Kirkpatrick model	Twenty-four articles were evaluated using Kirkpatrick's four-level model; outcomes varied according to gender and the type of knowledge assessed (factual versus spatial).

No.	Citation	Journal / Source	Study Design	Key Findings
4	(Bölek et al., 2021)*	Scientific Reports, 11	Systematic review and meta-analysis	AR was reported to reduce cognitive load while increasing student motivation and engagement; however, effects on learning outcomes varied across studies.
5	(Odogwu et al., 2025)*	PubMed Central, PMC12061000	Systematic review following PRISMA and Cochrane guidelines	A search across six databases covering studies published between 2019 and 2024 was conducted using the PICOS framework and Cochrane risk-of-bias assessment. VR was equivalent or superior on several outcomes, although substantial heterogeneity was observed.
6	(Adnan et al., 2025)*	Anatomical Sciences Education (PMC12051093)	Systematic review	Fifteen studies were included, with outcomes categorized into “knowledge” (retention and acquisition) and “perceptions” (learning efficiency, interest, and spatial awareness).
7	(Asghar et al., 2022)*	PubMed Central, PMC9768753	Meta-analysis and trial sequential analysis	Twenty-two RCTs involving 1,435 participants demonstrated positive standardized mean differences for both factual knowledge acquisition and spatial orientation.
8	(Xie et al., 2025)*	BMC Medical Education, 25	Systematic review and meta-analysis of RCTs	Manipulation of 3D-printed models supported the development of spatial reasoning and understanding of anatomical relationships while also increasing learning motivation.
9	(Ye et al., 2023)*	Frontiers in Bioengineering and Biotechnology, 11	Meta-analysis	Three-dimensional printed models were effective in improving anatomical knowledge, with several studies directly comparing them with cadaveric and plastinated specimens.
10	(Ahmed, 2023)*	Cureus / PubMed Central, PMC10083048	Integrative review	The Anatomage Table was considered valuable for anatomy learning outcomes and was supported as an important complementary tool rather than a replacement for cadaveric dissection.
11	(Eirini-Maria et al., 2023)*	Cureus / PubMed Central, PMC10484354	Narrative review	Anatomage enables the rotation and magnification of anatomical structures from multiple perspectives and eliminates exposure to

No.	Citation	Journal / Source	Study Design	Key Findings
				chemical preservatives; however, it does not provide the emotional engagement associated with cadaveric learning.
12	(Asad et al., 2023)	Cureus, 15(4), e37713	Cross-sectional survey study	Cadaveric dissection was considered superior for demonstrating real anatomical variation and fostering professionalism and ethical awareness that cannot be fully replicated by digital media.
13	(Şişu et al., 2024)*	Education Sciences, 14(11), 1150	Student opinion survey and review	Approximately 57% of students continued to prefer cadaver-based learning, whereas 3D visualization technologies improved factual and spatial knowledge and enhanced user satisfaction.
14	(Roach et al., 2021)	Anatomical Sciences Education, 14(3), 317–329	Meta-analysis	Across 15 studies involving 1,245 participants, a weak but significant correlation was found between spatial ability and anatomy performance ($r = 0.240$; 95% CI = 0.09–0.38; $p = 0.002$), with stronger associations observed for practical and spatially oriented assessments.
15	(Bogomolova et al., 2023)	Anatomical Sciences Education, 16(1), 87–98	Two-centre RCT	Students learned lower-limb anatomy using either stereoscopic 3D AR ($n = 32$) or monoscopic visualization ($n = 34$). Knowledge acquisition and cognitive load were evaluated in relation to visuospatial ability measured using the Mental Rotation Test (MRT).
16	(Chytas et al., 2022)*	Anatomical Sciences Education, 15(6), 1152–1154	Critical commentary/analysis	Virtual learning environments may disadvantage students with lower spatial ability when assessment methods are not aligned with the learning modality.
17	(Sarilita et al., 2022)	Korean Journal of Medical Education, 34(4), 309–318	Cross-sectional study (Indonesia)	Students demonstrated moderate levels of spatial ability based on the PSVT-R and Vandenberg–Kuse MRT, with significant differences observed across gender and student cohorts.
18	(Nokovitch et al., 2025)	Medical Education	Systematic review	Interventions designed to improve visuospatial ability were associated with spatial anatomy learning, and all

No.	Citation	Journal / Source	Study Design	Key Findings
				assessment instruments used measured intrinsic–dynamic spatial skills.
19	(Sagoo et al., 2025)*	Anatomical Sciences Education	Quantitative study	The study examined whether spatial skills could be developed through anatomy instruction and also explored gender-related differences in spatial ability.
20	(Aspanani et al., 2023)	BMC Medical Education, 23(1), 336	Correlational study	Visual memory and spatial intelligence were associated with students' academic performance in anatomy courses.
21	(Lee & Zhang, 2025)*	Frontiers in Psychiatry, 16, 1684727	Systematic review	Up to one-third of medical students reported clinically meaningful symptoms of inattention, while structural support and institutional accommodations remained insufficient.
22	(Bailey et al., 2023)*	Medical education literature (review and pilot survey)	Literature review and survey	The neurodiversity paradigm is increasingly recognized in medical education, highlighting the need for evidence-based adaptive teaching strategies and standardized institutional support.
23	(Nejati et al., 2024)	Clinical Child Psychology and Psychiatry	Systematic review	Individuals with ADHD demonstrated slower visuospatial processing and weaknesses in visuoconstructive ability; however, evidence regarding specific deficits in mental rotation remained inconsistent.
24	(Parmar et al., 2026)*	Discover Education	Mixed-methods pilot study	Spatial AR visualization increased task salience and supported task initiation and planning while reducing perceived cognitive load through AI-based scaffolding.
25	(Wolfers et al., 2026)*	Sensors, 26(3), 1017	Multisensory experimental study	The study targeted university students with ADHD and integrated a VR head-mounted display with EEG to assess attention, cognitive load, and engagement using neurophysiological measures.
26	(Yang et al., 2025)*	Frontiers in Psychology, 16, 1613728	Intervention study using SEM	Multisensory AR improved attention and emotional regulation, whereas conventional classroom instruction relying heavily on

No.	Citation	Journal / Source	Study Design	Key Findings
				sustained attention appeared to exacerbate learning barriers.

Note: An asterisk () indicates entries for which the title, journal, and publication year were confirmed, whereas the first author's identity requires further verification during source retrieval because the record was initially identified through database metadata. All entries can be traced through the links provided in the accompanying reference document.*

3.3 Thematic Synthesis

a. Theme 1: The Effectiveness of Digital Spatial Modalities Compared with Cadaver-Based Learning

Digital spatial modalities, including 3D printing, virtual reality (VR), and augmented reality (AR), generally produce learning outcomes comparable to or better than conventional anatomy teaching, particularly for spatial understanding and knowledge acquisition. Meta-analytic evidence from 22 RCTs involving 1,435 participants demonstrated positive effects on factual knowledge and spatial orientation, while subsequent reviews showed that manipulating 3D models supports spatial reasoning and understanding of anatomical relationships. Similarly, VR and AR can enhance anatomy knowledge, reduce cognitive load, and improve motivation and engagement, although substantial heterogeneity warrants cautious interpretation. However, digital technologies do not fully replace cadaver-based learning, which uniquely provides exposure to authentic anatomical variation and supports professionalism and ethical awareness. Overall, the evidence favors a complementary rather than substitutive approach, with hybrid models integrating cadaver-based learning and digital spatial technologies representing the most pedagogically robust strategy.

b. Theme 2: Spatial Ability as a Predictor, Moderator, and Target of Intervention

Visuospatial ability plays a multidimensional role in anatomy education as a predictor of academic performance, a moderator of instructional effectiveness, and a potentially modifiable intervention target. Meta-analytic and correlational evidence links spatial ability and visual memory to anatomy performance, particularly in practical and spatially demanding tasks, while experimental studies indicate that mental rotation and visuospatial ability may influence knowledge acquisition and cognitive load in immersive environments such as stereoscopic AR. Recent evidence further suggests that spatial skills can be strengthened through targeted interventions and anatomy instruction, challenging the view that lower spatial ability is a fixed limitation. Nevertheless, technology does not automatically improve learning, as misalignment between learner characteristics, instructional tasks, learning modalities, and assessment strategies may disadvantage students with lower spatial ability.

c. Theme 3: ADHD-Related Cognitive Characteristics Relevant to Spatial Learning

ADHD appears to be associated with specific differences in visuospatial processing and executive functioning relevant to spatial anatomy learning rather than a generalized spatial deficit. Systematic review evidence indicates slower visuospatial processing and weaker visuoconstructive abilities, whereas evidence of specific mental-rotation impairments remains inconsistent. Combined with findings linking visual memory and spatial ability to anatomy performance, this suggests that tasks requiring extensive internal manipulation of spatial information may impose greater cognitive demands on some learners with ADHD. Externally represented and manipulable three-dimensional materials may therefore provide a compensatory mechanism by externalizing spatial information and reducing reliance on internal visuospatial working memory. However, this mechanism remains theoretical because no direct evidence has

yet demonstrated differential benefits of spatial anatomy technologies for medical students with ADHD.

d. Theme 4: Immersive Technologies and AR for Learners with ADHD: Cross-Domain Evidence

Cross-domain evidence suggests that immersive and interactive technologies may benefit learners with ADHD through multisensory stimulation, interactivity, increased task salience, and cognitive scaffolding. AR-based visualization and AI-supported scaffolding have been associated with improved task initiation and planning and reduced perceived cognitive load, while VR combined with neurophysiological measures offers potential for objectively assessing attention, cognitive load, and engagement among university students with ADHD. Evidence from younger populations similarly suggests that multisensory AR may support attention and emotional regulation compared with conventional instruction relying heavily on sustained attention and linear information delivery. These findings are conceptually consistent with ADHD-related cognitive characteristics and support the potential of immersive technologies as adaptive learning environments; however, because the evidence originates primarily from non-anatomical domains such as literacy, task management, and attention regulation, its applicability to spatial anatomy education remains inferential and requires direct investigation.

e. Theme 5: The Evidence Gap at the Intersection of ADHD and Spatial Anatomy Education

The most significant finding of this review is the absence of direct evidence at the intersection of ADHD, spatial cognition, and anatomy education. No identified study examined the effectiveness of VR, AR, Anatomage, or 3D printing specifically among medical students with ADHD through subgroup analyses or ADHD-based participant stratification. Digital anatomy studies generally focused on average learning outcomes without measuring or reporting neurodivergence, whereas ADHD research primarily addressed prevalence, institutional accommodations, attention regulation, and non-anatomical learning outcomes. Even studies examining spatial ability as a moderator focused on visuospatial competence rather than neurodivergent characteristics. This absence should not be interpreted as evidence of ineffectiveness but rather as an indication that the question remains substantially underexplored, providing a clear rationale for research examining whether spatial instructional technologies can support anatomy learning among neurodivergent students and whether individual cognitive characteristics contribute to heterogeneous responses across educational modalities.

3.4 Discussion

The integration of the five themes provides a coherent theoretical explanation of the relationship between digital spatial anatomy modalities, visuospatial ability, neurodiversity, and anatomy learning. Digital spatial modalities have generally demonstrated positive educational effects, particularly for spatial understanding and anatomy knowledge acquisition, while their effectiveness appears to be influenced by learners' visuospatial ability (Bogomolova et al., 2023; Salimi et al., 2024). Spatial ability is positively associated with anatomy performance (Roach et al., 2021) and visual memory (Aspanani et al., 2023). Because ADHD has been associated with differences in visuospatial processing speed and visuoconstructive ability (Nejati et al., 2024), learners with ADHD may theoretically benefit from external three-dimensional representations that reduce reliance on internal visuospatial working memory resources. This argument is further supported by evidence suggesting that AR may reduce cognitive load among learners with ADHD (Parmar et al., 2026) and within anatomy education (Bölek et al., 2021).

However, this interpretation requires careful qualification. ADHD should not be understood as a generalized spatial deficit because evidence regarding specific impairments in mental rotation remains inconsistent (Nejati et al., 2024); therefore, it cannot be assumed that all learners with ADHD have lower spatial ability. Moreover, virtual learning environments may disadvantage learners with lower spatial ability when assessment methods are poorly aligned with the instructional modality (Chytas et al., 2022). Excessive immersive stimulation may also increase extraneous cognitive load, potentially posing additional challenges for learners with vulnerable executive control. Accordingly, the relationship between immersion and learning outcomes may follow an inverted U shaped pattern, whereby interactivity and task salience are beneficial up to an optimal point, after which excessive sensory stimulation becomes counterproductive.

Based on this synthesis, several empirically testable propositions emerge. Interactive digital spatial modalities, such as AR and 3D printed models, may produce greater spatial knowledge acquisition than two-dimensional atlases among medical students with ADHD, potentially generating stronger effects than those observed among non-ADHD learners. The benefits of immersive VR may also depend on the level of sensory stimulation, with lower distraction designs potentially outperforming highly stimulus rich environments for learners with ADHD. Furthermore, any advantage associated with digital modalities may operate through reductions in cognitive load, which could be examined using both subjective measures and neurophysiological indicators. Finally, hybrid approaches combining cadaver-based learning with digital modalities may support superior long term retention compared with single modality instruction, particularly among neurodivergent learners. These propositions remain hypotheses rather than established conclusions and therefore require direct empirical testing.

The findings also have important practical implications for anatomy education. They support the application of the Universal Design for Learning framework by providing multiple means of representation, including cadavers, digital three-dimensional visualization, and physical models, alongside multiple means of engagement and expression through assessment. Rather than positioning digital technologies solely as specialized accommodations for a limited group of students, institutions could provide them as universally accessible learning options that may benefit diverse learners, particularly those with lower spatial ability or neurodivergent characteristics, while simultaneously reducing stigma and the need for diagnostic disclosure. (Roach et al., 2021) recommended adapting curriculum delivery and assessment strategies to avoid disadvantaging learners with lower spatial ability, an approach that may reasonably be extended to students with ADHD. Nevertheless, the caution raised by (Chytas et al., 2022) remains critical: alignment between instructional modalities and assessment methods is essential because misalignment may transform potential technological benefits into educational disadvantages.

Several limitations should also be considered when interpreting these findings. First, this review employed a narrative thematic synthesis and did not generate pooled effect estimates because substantial heterogeneity in instructional modalities, outcome measures, and study designs precluded a meaningful meta-analysis. Second, the absence of direct evidence at the intersection of ADHD and anatomy education required inferences from indirect evidence by integrating research on modality effectiveness with ADHD related cognitive findings from different domains. These inferences should therefore not be considered equivalent to direct empirical evidence. Third, restricting the review to studies published between 2021 and 2026 improved the currency of the evidence but excluded some foundational studies, including earlier randomized controlled trials involving 3D printed models and studies examining visuospatial moderation published between 2018 and 2020, thereby limiting historical depth. Fourth, restricting the review to English and Indonesian language publications may have introduced selection bias. Finally, most studies

investigating anatomy learning modalities did not report participants' neurodivergence status, making it impossible to evaluate potential subgroup effects even retrospectively.

These limitations directly inform the future research agenda. Randomized controlled and quasi experimental studies should screen for and stratify ADHD status while measuring baseline visuospatial ability as a covariate; the approach used by (Bogomolova et al., 2023), which integrates knowledge acquisition, cognitive load, and mental rotation measures, provides a useful methodological model. Future studies should also incorporate objective indicators of cognitive load, including EEG based approaches such as those demonstrated in (Wolfers et al., 2026), to test whether digital spatial representations reduce working memory demands. Comparative design studies examining different levels of immersion and sensory stimulation are also needed to identify optimal configurations for neurodivergent learners and empirically test the proposed inverted U-shaped relationship. Finally, research conducted in Indonesia could examine the relationship among spatial ability, neurodiversity, and anatomy learning modalities by extending the findings of (Sarilita et al., 2022) to medical student populations while incorporating ADHD screening. Addressing these priorities would help move the field from theoretically plausible but indirect inferences toward robust evidence on how individual cognitive characteristics shape responses to different anatomy learning modalities.

4. CONCLUSION

This systematic review of 26 studies published between 2021 and 2026 indicates that digital spatial anatomy modalities, including VR, AR, the Anatomage Table, and 3D printing, generally produce learning outcomes comparable to or superior to conventional methods for both factual and spatial anatomy knowledge, with effectiveness moderated by learners' baseline visuospatial ability. In relation to cadaver based learning, the evidence supports a complementary rather than substitutive role: students and educators continue to value cadaveric dissection for its representation of authentic anatomical variation, haptic experience, and contribution to professional development, making hybrid instructional models the most strongly supported practical approach.

From a neurodiversity perspective, ADHD is associated with differences in visuospatial processing speed and visuoconstructive ability, although not with a generalized spatial deficit. Recent cross domain evidence further suggests that AR and VR may reduce cognitive load and increase task salience among learners with ADHD. Nevertheless, no direct evidence was identified examining spatial anatomy modalities specifically among medical students with ADHD, representing a clear and consistent gap across the reviewed literature.

Indirect evidence supports the hypothesis that interactive digital modalities capable of externalizing spatial information and reducing working memory demands may benefit learners with ADHD, consistent with the principles of Universal Design for Learning. However, these potential benefits depend on appropriate alignment between learning modalities and assessment design and on maintaining an optimal level of sensory stimulation. Controlled studies that stratify ADHD status and objectively measure visuospatial ability and cognitive load are therefore needed to transform this theoretical inference into robust empirical evidence.

REFERENCES

- Adnan, S., Benson, A. C., & Xiao, J. (2025). How virtual reality is being adopted in anatomy education in health sciences and allied health: A systematic review. *Anatomical Sciences Education*, 18(5), 496–525. <https://doi.org/https://doi.org/10.1002/ase.70027>
- Ahmed, M. A. A. S. (2023). Use of the Anatomage virtual table in medical education and as a diagnostic tool: an integrative review. *Cureus*, 15(3). <https://doi.org/https://doi.org/10.7759/cureus.35981>

- Asad, M. R., Asghar, A., Tadv, N., Ahmed, M. M., Nazeer, M., Amir, K. M., Nasir, N., Shaik, R. A., Patra, A., & Asad, M. R. (2023). Medical faculty perspectives toward cadaveric dissection as a learning tool for anatomy education: a survey study in India. *Cureus*, 15(4). <https://doi.org/https://doi.org/10.7759/cureus.37713>
- Asghar, A., Naaz, S., Patra, A., Ravi, K. S., & Khanal, L. (2022). Effectiveness of 3D-printed models prepared from radiological data for anatomy education: A meta-analysis and trial sequential analysis of 22 randomized, controlled, crossover trials. *Journal of Education and Health Promotion*, 11, 353. https://doi.org/https://doi.org/10.4103/jehp.jehp_199_22
- Aspanani, A., Sadeqhi, H., & Omid, A. (2023). The relationship between visual memory and spatial intelligence with students' academic achievement in anatomy. *BMC Medical Education*, 23(1), 336. <https://doi.org/https://doi.org/10.1186/s12909-023-04327-9>
- Bailey, A., Grotowski, M., & Bailey, S. (2023). Medical education: Accommodating students with ADHD. *Medical Teacher*, 46, 1–6. <https://doi.org/10.1080/0142159X.2023.2287984>
- Bogomolova, K., Vorstenbosch, M. A. T. M., El Messaoudi, I., Holla, M., Hovius, S. E. R., van der Hage, J. A., & Hierck, B. P. (2023). Effect of binocular disparity on learning anatomy with stereoscopic augmented reality visualization: A double center randomized controlled trial. *Anatomical Sciences Education*, 16(1), 87–98. <https://doi.org/https://doi.org/10.1002/ase.2164>
- Bölek, K. A., De Jong, G., & Henssen, D. (2021). The effectiveness of the use of augmented reality in anatomy education: a systematic review and meta-analysis. *Scientific Reports*, 11(1), 15292. <https://doi.org/10.1038/s41598-021-94721-4>
- Chytas, D., Salmas, M., Demesticha, T., & Troupis, T. G. (2022). Can virtual environments be detrimental for anatomy education of students with low spatial ability? The important role of assessment methods. *Anatomical Sciences Education*, 15(6), 1152–1154. <https://doi.org/https://doi.org/10.1002/ase.2185>
- Eirini-Maria, K., Ioanna, K., Stavros, A., & Dimitrios, F. (2023). The anatomage table: A promising alternative in anatomy education. *Cureus*, 15(8). <https://doi.org/https://doi.org/10.7759/cureus.43047>
- García-Robles, P., Cortés-Pérez, I., Nieto-Escámez, F. A., García-López, H., Obrero-Gaitán, E., & Osuna-Pérez, M. C. (2024). Immersive virtual reality and augmented reality in anatomy education: a systematic review and Meta-Analysis. *Anatomical Sciences Education*, 17(3), 514–528. <https://doi.org/https://doi.org/10.1002/ase.2397>
- Lee, N. Y. W., & Zhang, M. W. Bin. (2025). Systematic review on prevalence of ADHD, possible ADHD or ADHD symptoms in medical students. *Frontiers in Psychiatry*, 16, 1684727. <https://doi.org/https://doi.org/10.3389/fpsy.2025.1684727>
- Minouei, M. A., Omid, A., Mirzaie, A., Mahdavi, H., & Rahimi, A. (2024). Effectiveness of virtual reality on medical students' academic achievement in anatomy: systematic review. *BMC Medical Education*, 24(1), 1407. <https://doi.org/10.1186/s12909-024-06402-1>
- Nejati, V., Khoshroo, S., & Mirikaram, F. (2024). Review of spatial disability in individuals with attention deficit-hyperactivity disorder: Toward spatial cognition theory. *Clinical Child Psychology and Psychiatry*, 29(1), 312–337. <https://doi.org/https://doi.org/10.1177/13591045231176707>
- Nokovitch, L., El Hajj, H., Deneuve, S., De Andrade, V., Gagnayre, R., & Margat, A. (2025). Visual-spatial abilities enhancement and spatial anatomy learning: A systematic review. *Medical Education*, 59(12), 1322–1332. <https://doi.org/https://doi.org/10.1111/medu.70022>
- Odogwu, T. S., Mohamed, E. A. H., Mishu, L., & Umahi, I. (2025). Effect of virtual reality simulation on anatomy learning outcomes: a systematic review. *Cureus*, 17(4). <https://doi.org/https://doi.org/10.7759/cureus.81893>
- Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., Shamseer, L., Tetzlaff, J. M., Akl, E. A., & Brennan, S. E. (2021). The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. *Bmj*, 372. <https://doi.org/https://doi.org/10.1136/bmj.n71>

- Parmar, R., Oyelere, S. S., & Aruleba, K. (2026). A user-centred approach to enhancing engagement and task management for ADHD students using AR and generative AI. *Discover Education*, 5(1), 235. <https://doi.org/https://doi.org/10.1007/s44217-026-01264-9>
- Roach, V. A., Mi, M., Mussell, J., Van Nuland, S. E., Lufner, R. S., DeVeau, K. M., Dunham, S. M., Husmann, P., Herriott, H. L., & Edwards, D. N. (2021). Correlating spatial ability with anatomy assessment performance: A meta-analysis. *Anatomical Sciences Education*, 14(3), 317–329. <https://doi.org/https://doi.org/10.1002/ase.2029>
- Sagoo, M. G., Lam, P. Y., Theivendran, S., & Wingate, R. (2025). Exploring the potential malleability of spatial skills through anatomy teaching: A quantitative study among medical students. *Anatomical Sciences Education*, 18(9), 961–971. <https://doi.org/https://doi.org/10.1002/ase.70071>
- Salimi, S., Asgari, Z., Mohammadnejad, A., Teimazi, A., & Bakhtiari, M. (2024). Efficacy of virtual reality and augmented reality in anatomy education: a systematic review and meta-analysis. *Anatomical Sciences Education*, 17(9), 1668–1685. <https://doi.org/https://doi.org/10.1002/ase.2501>
- Sarilita, E., Lita, Y. A., Firman, D. R., Wilkinson, T., Susilawati, S., Saptarini, R., Aripin, D., & Sjamsudin, E. (2022). Spatial ability and anatomy learning performance among dental students. *Korean Journal of Medical Education*, 34(4), 309. <https://doi.org/https://doi.org/10.3946/kjme.2022.239>
- Șișu, A. M., Stoicescu, E. R., Bolintineanu, S. L., Faur, A. C., Iacob, R., Ghenciu, D. M., Dănilă, A.-I., & Hațegan, O. A. (2024). Blending tradition and innovation: student opinions on modern anatomy education. *Education Sciences*, 14(11), 1150. <https://doi.org/https://doi.org/10.3390/educsci14111150>
- Wolfers, J., Hurst, W., & Krampe, C. (2026). Integrating EEG Sensors with Virtual Reality to Support Students with ADHD. *Sensors*, 26(3), 1017. <https://doi.org/https://doi.org/10.3390/s26031017>
- Xie, G., Wang, T., Fu, H., Liu, D., Deng, L., Zheng, X., Li, L., & Liao, J. (2025). The role of three-dimensional printing models in medical education: a systematic review and meta-analysis of randomized controlled trials. *BMC Medical Education*, 25(1), 826. <https://doi.org/10.1186/s12909-025-07187-7>
- Yang, R., Sun, W., Liu, X., & Cao, Y. (2025). Enhancing attention and emotion regulation in children with ADHD through AR digital picture books: a structural equation modeling approach. *Frontiers in Psychology*, 16, 1613728. <https://doi.org/https://doi.org/10.3389/fpsyg.2025.1613728>
- Ye, Z., Jiang, H., Bai, S., Wang, T., Yang, D., Hou, H., Zhang, Y., & Yi, S. (2023). Meta-analyzing the efficacy of 3D printed models in anatomy education. *Frontiers in Bioengineering and Biotechnology*, 11, 1117555. <https://doi.org/https://doi.org/10.3389/fbioe.2023.1117555>