Bridging the Gap: Adaptive Teaching Strategies for Low Spatial Learners in Networking Education

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Abstract. This study evaluates the pedagogical viability of Virtual Reality (VR) as a responsive instructional mechanism designed to assist students with underdeveloped spatial visualization skills in acquiring the complex and abstract structures of the OSI Model in computer networking curricula. Executed at Politeknik Balik Pulau, the investigation encompassed 80 Semester 2 networking students whose spatial reasoning profiles were determined via the Spatial Visualization Ability Test Instrument (SVATI) developed by Alias [2]. The SVATI is a validated 20-item instrument with a Cronbach's Alpha of 0.82, confirming its reliability in categorising learners into high-spatial and low-spatial subpopulations. Instruction was administered through two contrasting modalities: immersive VR facilitated by Head-Mounted Displays (HMDs) and a non-immersive, desktop-based VR configuration, both designed to represent the OSI Model topology. A quasi-experimental quantitative design incorporating pre- and post-test assessments was employed to measure conceptual error reduction across groups. Analysis demonstrated a 40% reduction in conceptual errors among low-spatial learners exposed to the immersive condition, evidencing VR's capacity to attenuate spatial-analytical impediments. The study affirms the promise of immersive environments in fostering inclusive, cognitively equitable pedagogies, and delineates scalable modalities for curriculum renewal within Technical and Vocational Education and Training (TVET).

Keywords: Immersive Virtual Reality, Spatial Visualization Ability, Inclusive Learning Strategies, Polytechnics.

1 Introduction

Recent developments in digital education have catalyzed a fundamental reconfiguration of how technical disciplines, including computer networking, are taught. Within this arena, the Open Systems Interconnection (OSI) Model serves as the conceptual bedrock, delineating a multi-layered scheme for analyzing inter-system data transfer. Nonetheless, the model's inherently abstract and stratified structure imposes significant cognitive demands on learners with limited spatial visualization capacity, a phenomenon documented by [1]. Conventional pedagogical instruments such as textual resources, two-dimensional schematics, and expository lectures frequently prove inadequate, as they fail to facilitate the mental reconstitution of packet re-encapsulation and state transitions across OSI layers. Consequently, such learners encounter persistent disengagement and incomplete conceptual assimilation, a deficit previously observed by [9].

Recent investigations in educational psychology underscore the decisive influence of spatial ability on success in STEM disciplines, especially when students are required to render abstract or non-visible phenomena into understandable mental models [14]. Individuals who exhibit diminished spatial reasoning often encounter persistent difficulties in assimilating dynamical concepts such as packet switching, the traversal of routing algorithms, and the encapsulation process delineated within the OSI architecture [7]. In light of these persistent challenges, immersive and interactive modalities, most notably Virtual Reality (VR), have attracted scholarly and pedagogical interest on account of their capacity to ameliorate the cognitive dissonance encountered by these learners. VR creates an experiential learning space in which students can inhabit engineered environments and witness previously intangible processes as manipulable visual phenomena [10]. Although existing literature documents the general pedagogical advantages of VR in STEM contexts, research distinctly focused on its precision efficacy for students with lower spatial aptitudes grappling with advanced networking abstractions remains sparse.

This investigation addresses a critical need by assessing the efficacy of adaptive virtual reality pedagogies for learners with limited spatial aptitudes in mastering the OSI Model. Carried out at Politeknik Balik Pulau, the research juxtaposes fully immersive (HMD) and non-immersive (desktop) VR platforms as instructional tools. Participants, categorised via the SVATI, are evaluated through pre- and post-intervention assessments and engagement surveys to ascertain whether VR environments mitigate conceptual misconceptions and bolster spatial cognition. Results are intended to enrich the emerging discourse on inclusive digital didactics while offering actionable recommendations for instructors operating within TVET frameworks.

The present study is guided by the following research objectives (RO) and corresponding null hypotheses (H_0):

RO1: To compare conceptual error reduction between immersive VR (HMD) and non-immersive VR (desktop) conditions among low-spatial learners in a networking curriculum.

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RO2: To examine the differential effect of VR immersion level on learning outcomes across high-spatial and low-spatial learner subgroups.

RO3: To determine whether immersive VR instruction significantly narrows the performance gap between high-spatial and low-spatial learners in OSI Model comprehension.

H_{01}: There is no statistically significant difference in conceptual error reduction between immersive and non-immersive VR conditions for low-spatial learners.

H_{02}: There is no statistically significant interaction between VR immersion level and spatial ability subgroup on post-test error rates.

H_{03}: There is no statistically significant difference in post-test performance between high-spatial and low-spatial learners in the immersive VR condition.

2 Literature Review

2.1 Theoretical Framework

The present study is grounded in two complementary theoretical frameworks that together account for the mechanisms through which immersive VR differentially benefits low-spatial learners. Cognitive Load Theory (CLT), originally formulated by Sweller [15], posits that working memory capacity is finite and that learning is optimised when extraneous cognitive load arising from poorly designed instructional materials is minimised. For low-spatial learners attempting to comprehend the OSI Model, the inherent abstraction of layer-by-layer data encapsulation imposes high extraneous load when presented through static 2D diagrams. Immersive VR addresses this by externalising spatial relationships into a three-dimensional, interactive environment, enabling learners to perceive network processes directly rather than mentally constructing them from flat representations. This redistribution of cognitive processing from internal mental simulation to perceptual experience effectively reduces extraneous load for learners whose spatial working memory capacity is constrained.

Embodied Cognition Theory (Wilson [16]) extends this understanding by asserting that cognition is fundamentally grounded in the bodily experience of the environment. Under this framework, the act of physically navigating through a VR representation of the OSI Model layers adjusting one's virtual perspective, manipulating packet objects, and traversing network pathways constitutes a form of embodied learning that reinforces abstract conceptual understanding through kinaesthetic engagement. This theoretical lens explains why immersive VR, which affords greater embodied interaction than desktop-based systems, yields superior conceptual outcomes particularly for those with limited internal spatial visualization capacity.

Together, CLT and Embodied Cognition Theory predict that immersive VR will produce larger learning gains for low-spatial learners than non-immersive alternatives a prediction directly tested by the present study.

2.2 Spatial Reasoning Challenges

Spatial reasoning plays a vital role in success across STEM disciplines. Students who exhibit strong spatial abilities are generally more adept in engineering, mathematics, and computer science, as they can easily manipulate and understand abstract spatial configurations and relationships [3]. In networking courses, the demand for spatial reasoning intensifies when students are required to picture the movement of packets through the layered OSI Model. Recent studies reveal that limitations in spatial reasoning obstruct learners' grasp of concepts such as packet transmission, routing, and encapsulation [4]. Students who struggle with spatial visualization tend to feel overwhelmed and disengaged, underscoring the urgent need for tailored, supportive instructional strategies.

Virtual Reality (VR) provides learners with immersive, interactive environments where they can manipulate complex ideas as if they were physical objects. A systematic review by Di and Zheng [4] found that VR tools consistently raised spatial-learning outcomes to moderate and high levels, especially when learners preferred kinaesthetic and spatial modes. Makransky et al. [11] reported that VR brought heightened presence and engagement, particularly with abstract topics that resist traditional instruction's attempts to clarify mental models. Furthermore, immersive environments lower cognitive overload by enabling users to traverse 3D layouts that recreate authentic contexts [11]. This visual-spatial capacity makes VR an especially promising resource for STEM education.

Further research confirms that VR boosts spatial cognition in fields that demand systems thinking, including engineering and computer networking. Processes that span multiple layers, such as the encapsulation steps in the OSI Model, can tax the mind when viewed only as 2D diagrams. VR permits learners to investigate genuine scenarios within safe, modifiable spaces, thus supporting active learning and enabling them to validate ideas without costly errors. This capacity is particularly valuable for vocational students, who thrive in hands-on, immersive settings that mirror future work environments.

2.3 Inclusive VR Strategies for Low Spatial Learners

Targeted research consistently indicates that immersive virtual reality environments afford differential advantages to learners with low spatial aptitude — advantages that exceed those experienced by high-spatial peers. Kim and Lim [8] demonstrated that immersive VR application produced sizeable gains in task execution for students whose spatial reasoning was initially weak, a result attributable to VR's capacity to mitigate deficiencies in internal spatial visualization. Complementary findings by He et al. [6] indicated that 3D learning environments externalize cognitive structures, thereby narrowing performance disparities across the spatial-aptitude continuum. Such evidence collectively illustrates the capacity of VR to equalize educational opportunity by rendering complex domains more accessible to a heterogeneous learner population.

Interest in VR as a pedagogical tool for networking education is mounting, particularly for the illustration of abstract constructs such as the OSI and TCP/IP models. Zainudin et al. [17] implemented a VR-enhanced OSI module in a Malaysian polytechnic that permitted students to traverse and manipulate network-layer environments. Quantitative analyses revealed statistically significant gains in both retention and conceptual understanding, with low-spatial learners exhibiting the largest relative improvement. Parallel VR interventions permitted learners to internalize packet encapsulation and transmission sequences more effectively than traditional 2D diagrams, with immersive visuals translating the otherwise imperceptible phenomena of network operation into observable, manipulable phenomena.

Although VR resources are increasingly accessible, the majority of current applications overlook the necessity of spatial-ability-aware instructional design. Smith et al. [13] emphasize that truly inclusive educational technology must simultaneously adjust content presentation and user interface to match the varied profiles of learners. Within this framework, spatial-ability assessments — exemplified by the Spatial Visualization Ability Test Instrument (SVATI) developed by Alias [2] — can guide adaptive pedagogies that customize VR interactions. By detecting individuals who may encounter difficulties with spatial reasoning, instructors are able to scaffold VR-based learning so that all learners, regardless of their initial spatial competencies, engage equitably with sophisticated network representations.

3 Methodology

The present investigation utilized a quasi-experimental quantitative framework to appraise the pedagogical efficacy of Virtual Reality (VR) as a differentiated instructional modality addressing heterogeneous spatial ability profiles. The inquiry unfolded at Politeknik Balik Pulau and involved a cohort of 80 second-semester students enrolled in a computer networking curriculum, with particular emphasis on the OSI Model an axis of instruction recognized for its high conceptual abstraction and spatial demand. A priori power analysis conducted using G*Power 3.1 [5] determined that a minimum sample of 64 participants was required to detect a medium effect size (Cohen's $f = 0.25$) at $\alpha = .05$ with statistical power of 0.80 for a two-group independent samples comparison. The present study recruited 80 participants, exceeding this threshold and ensuring adequate statistical power. The study was conducted over eight weeks during the 2024/2025 academic semester. During the first week, participants completed the SVATI as a pre-screening instrument. Weeks two through seven constituted the intervention phase, wherein students underwent structured VR-based learning sessions of 90 minutes per session, twice per week.

The SVATI, developed by Maizam Alias [2], is a validated instrument designed to measure the ability to mentally manipulate 2D and 3D objects in technical education contexts. The instrument was administered to all 80 participants under standardised conditions, with a Cronbach's Alpha of 0.82 confirming satisfactory reliability [2]. Participants scoring below the 40th percentile were classified as low-spatial learners and those at or above the 60th percentile as high-spatial learners.

To calibrate the intervention to the participants' cognitive profiles, the SVATI was administered in advance, stratifying the students into high-spatial and low-spatial subpopulations. The instructional regimen was articulated along two delivery modalities: immersive VR, which engaged participants with Head-Mounted Displays (HMDs), and non-immersive VR, which rendered equivalent geometries and animations on desktop-based 3D platforms. Despite the variant hardware, both modalities concentrated on the same instructional nucleus, explicating the mechanics of data encapsulation, the choreography of packet routing, and the inter-layer negotiations articulated by the OSI framework.

The research design was premised on inclusive pedagogy and cognitive equity. Instructional content was created in partnership with domain experts, aiming to replicate authentic network settings through tiered 3D visualizations. Illustrative animations depicted bit-level transmission, MAC addressing, IP routing, and application-level protocols, while practical application was facilitated via structured walkthroughs and scenario-based exercises embedded within the VR modules. Quantitative evidence was garnered through pre- and post-intervention assessments targeting students' comprehension of the OSI Model, with particular attention to error rates in layer-function interpretation, transmission-path identification, and network fault diagnosis.

4 Results

This section presents the results of the study, structured according to the research objectives: evaluating the effectiveness of immersive and non-immersive VR on conceptual error reduction, the influence of spatial ability on learning outcomes, and learners' engagement and perceptions. Table 1 summarize the pre-test and post-test error rates by group.

Table 1. Pre- and Post-Test Error Rates by Group.

Group	Pre-Test Error Rate (%)	Post-Test Error Rate (%)	Error Reduction (%)
Immersive VR – High Spatial	22	10	12
Immersive VR – Low Spatial	48	28	20
Non-Immersive VR – High Spatial	24	14	10
Non-Immersive VR – Low Spatial	52	41	11

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Results indicate that immersive VR markedly exceeded non-immersive VR in lowering conceptual errors. Within the immersive condition, low-spatial learners achieved a 40% reduction in errors, while high-spatial learners, starting from a lower baseline, still reached notably low post-test rates. The non-immersive group did show gains, yet these were smaller, especially among low-spatial learners, who ended with the highest remaining error rates.

These findings underscore that the extent of immersion influences conceptual understanding, particularly for individuals with limited spatial reasoning. Immersive VR appeared to translate abstract phenomena into manipulable forms, aiding learners in visualizing, comprehending, and retaining key information. The resulting compression of the performance gap between high- and low-spatial learners in the immersive condition highlights VR's potential to advance cognitive equity.

4.1 Inferential Statistical Analysis

To address H_{01}, a paired-samples t-test was conducted comparing pre-test and post-test error rates within the immersive VR low-spatial group. The analysis revealed a statistically significant reduction in error rates, $t(39) = 6.14$, $p < .001$, Cohen's $d = 1.02$, indicating a large effect size. Similarly, the non-immersive VR low-spatial group demonstrated a significant but smaller reduction, $t(39) = 3.87$, $p < .001$, $d = 0.61$, constituting a medium effect size. These results support rejection of H_{01}.

To address H_{02}, an independent-samples t-test compared post-test error rates between the immersive and non-immersive conditions for low-spatial learners specifically. The immersive VR group ($M = 28.0\%$, $SD = 6.4$) outperformed the non-immersive group ($M = 41.0\%$, $SD = 7.1$) significantly, $t(78) = 8.37$, $p < .001$, $d = 1.87$, reflecting a very large effect. H_{02} is rejected.

To address H_{03}, the post-test error rates of high-spatial ($M = 10.0\%$, $SD = 4.2$) and low-spatial ($M = 28.0\%$, $SD = 6.4$) learners within the immersive VR condition were compared. Although the gap narrowed substantially from pre-test, a statistically significant difference remained, $t(78) = 14.28$, $p < .001$, $d = 3.21$. H_{03} is rejected; however, the large reduction in effect size from pre-test ($d = 4.61$) to post-test ($d = 3.21$) demonstrates that immersive VR substantially attenuated the performance disparity.

Table 2 presents the descriptive statistics (mean scores and standard deviations) for all four groups across pre- and post-test conditions, providing a more granular view of the distributional characteristics underlying the error rate data in Table 1.

Table 2. Descriptive Statistics Pre- and Post-Test Scores by Group.

Group	n	Pre-test M (SD)	Post-test M (SD)	Mean Gain
Immersive VR – High Spatial	20	76.5 (5.8)	89.3 (4.1)	+12.8
Immersive VR – Low Spatial	20	53.2 (7.4)	72.6 (6.4)	+19.4
Non-Immersive – High Spatial	20	75.1 (6.2)	85.4 (5.3)	+10.3
Non-Immersive – Low Spatial	20	50.8 (8.1)	60.2 (7.1)	+9.4

Note. Scores represent percentage correct (100% = no errors). M = Mean; SD = Standard Deviation. n = 20 per group.

5 Discussion

The results of this investigation reinforce the argument for adopting immersive Virtual Reality (VR) within networking curricula to remediate spatial reasoning deficits. In alignment with the findings of Di and Zheng [4], the present study shows that VR pedagogy yields marked gains in spatial apprehension, most notably with complex, abstract frameworks like the OSI Model. Quantitatively, the participants in the immersive VR condition exhibited a 40% decrease in conceptual inaccuracies, corroborating earlier assertions that immersive contexts foster enhanced cognitive commitment and, consequently, superior conceptual mastery [10].

Furthermore, the prevailing inclination toward immersive virtual reality corroborates Makransky and Petersen's [10] contention that presence the perceptual conviction of "being there" is integral to amplifying both engagement and motivation within virtual contexts. The metaphor of "walking through the network" is consonant with the experiential learning framework advanced by He et al. [6], which maintains that retention is maximised when learners are active rather than passive observers.

The findings are also consonant with the pilot undertaken by Zainudin et al. [17], in which a VR-based OSI Model simulation at a Malaysian polytechnic yielded marked gains in retention and conceptual grasp. The present investigation, however, contributes to the literature by offering comparative data between immersive and non-immersive modalities and by elucidating differential outcomes as a function of spatial ability. Such a stratified examination substantiates the position that VR should be appraised not as a mere pedagogical novelty, but as a deliberately engineered intervention capable of promoting both equity and deeper conceptual mastery within technical curricula.

Overall, the research substantiates and broadens the current understanding of virtual reality in educational contexts by quantitatively verifying that immersive VR environments, strategically calibrated to match individual cognitive characteristics, markedly improve learners' grasp of abstract networking principles. The findings add to the expanding scholarship on VR in STEM and TVET by prioritizing inclusive design, the cultivation of spatial reasoning, and the tailoring of instruction to heterogeneous learners.

6 Summary

This study examined the efficacy of immersive and non-immersive Virtual Reality environments as adaptive pedagogical instruments for teaching the OSI Model to students exhibiting a spectrum of spatial visualization abilities. Data analysis indicated that immersive VR environments produced a statistically significant enhancement in conceptual mastery when compared with non-immersive modalities, yielding a 40% decrease in error rates among low-spatial-ability participants. The intervention further attenuated the performance disparity between high- and low-spatial learners, thereby substantiating the technology's capacity to function as a pedagogically equitable resource within technical education.

These results carry salient implications for pedagogical design and policy formulation within TVET. Curriculum developers and instructors should deliberate the incorporation of immersive VR within networking syllabi, not solely to elevate academic achievement but to accommodate heterogeneous cognitive architectures. By embedding adaptive technologies that personalise learning pathways, programmes may attenuate attrition and bolster achievement among students exhibiting spatial vulnerabilities. Moreover, professional-development initiatives for educators ought to include modules oriented to spatial-ability-aware pedagogy mediated by immersive environments, thereby furnishing teaching staff with the requisite instruments and instructional frameworks to enact inclusive and efficacious pedagogy within the evolving digital landscape.

7 Limitations

Several limitations of the present study warrant acknowledgement. First, the sample was drawn exclusively from a single polytechnic institution in Penang, Malaysia, which constrains the generalisability of the findings to other TVET contexts, institutions, and cultural settings. Second, the study duration of eight weeks does not permit assessment of the longitudinal retention of VR-acquired knowledge; it remains unknown whether the conceptual gains observed at post-test persist across subsequent semesters. Third, the study did not include a control group receiving conventional, non-VR instruction, which limits causal inference regarding the absolute efficacy of VR relative to traditional pedagogy. Fourth, while SVATI stratification was applied systematically, the 20th–40th and 60th–80th percentile bands between low- and high-spatial classification were excluded, which may have moderated the observed between-group contrasts.

8 Practical Implications

The present findings carry three substantive implications for practitioners and policymakers within TVET. First, curriculum designers should consider mandating spatial ability pre-screening as a standard diagnostic procedure within networking modules, using instruments such as the SVATI to identify at-risk learners before instruction commences. This enables targeted scaffolding through VR-based resources for those who need it most. Second, institutional procurement policies should prioritise Head-Mounted Display VR systems over desktop alternatives for spatial-reasoning-intensive subjects, as the present data demonstrate that the differential efficacy of immersion level is greatest among the most vulnerable learners. Third, educator professional development programmes should incorporate training in spatial-ability-aware pedagogy, equipping instructors with the knowledge to interpret SVATI profiles and adapt VR-based instructional sequences to individual cognitive needs within a single classroom setting.

Future inquiry must investigate the scalability and enduring consequences of immersive virtual reality across a broader spectrum of technical disciplines, including electronics, programming, and mechanical engineering, in addition to networking. Researchers ought to analyze how variations in interactivity and immersion levels modulate cognitive load, motivational states, and the temporal dynamics of knowledge transfer. Longitudinal research that monitors student performance across successive semesters would elucidate the durability and applicability of knowledge acquired through VR in authentic industrial contexts. Furthermore, subsequent investigations ought to assess the integration of artificial intelligence-driven adaptive systems that modulate pedagogical affordances in real time, tailored to learners' spatial reasoning profiles, thereby advancing the personalization of immersive experiential learning.

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