

Enhancing Students' Understanding of Routing Protocols - Using Cisco Packet Tracer Simulation : A Pedagogical Intervention for Networking Courses

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Abstract— Routing protocols such as Routing Information Protocol (RIP), Open Shortest Path First (OSPF), and Enhanced Interior Gateway Routing Protocol (EIGRP) are fundamental topics in computer networking education but are often difficult for students to master through traditional lecture-based methods. Their dynamic and distributed nature requires practical exposure to enhance understanding. Cisco Packet Tracer, a network simulation platform developed by Cisco Systems, provides an interactive environment for configuring, observing, and troubleshooting routing protocols without the need for costly physical laboratory infrastructure. This study evaluated the effectiveness of Cisco Packet Tracer simulation-based instruction in improving undergraduate students' understanding of routing protocols. A quasi-experimental pre-test/post-test control group design was adopted involving 186 students enrolled in Computer Networks courses across two institutions. The experimental group ($n = 94$) participated in six structured Packet Tracer laboratory sessions covering RIP v2, OSPF, and EIGRP, while the control group ($n = 92$) received conventional instruction supported by textbooks and static diagrams. Student performance was assessed using a validated Routing Protocol Knowledge Assessment (RPKA), while motivation was measured using an adapted Instructional Materials Motivation Survey (IMMS). Results showed that the experimental group achieved significantly higher post-test scores than the control group (74.3 vs. 61.8; $p < 0.001$), with a large effect size ($d = 1.23$). The greatest improvement occurred in diagnostic reasoning skills ($d = 1.38$). Knowledge retention was also significantly higher in the experimental group after six weeks (71.6 vs. 55.2; $p < 0.001$). Additionally, students exposed to Packet Tracer reported higher motivation, particularly in relevance and confidence. The findings demonstrate that Cisco Packet Tracer is an effective and accessible tool for enhancing learning, retention, and engagement in routing protocol education.

Keywords: *Cisco Packet Tracer; routing protocols; RIP; OSPF; EIGRP; network simulation; computer networking education; undergraduate learning; instructional technology; student performance.*

I. INTRODUCTION

Computer networking has become a foundational discipline in information and communication technology (ICT) education, providing the conceptual and practical underpinnings for careers in network administration, cybersecurity, cloud computing and systems engineering. Within this discipline, routing protocols occupy a central and particularly challenging position: they define the mechanisms by which routers dynamically discover, share and select paths through interconnected networks, and their behaviour distributed, asynchronous, convergence-dependent and often counterintuitive is notoriously difficult to convey through static instructional media (Kurose & Ross, 2022; Forouzan, 2018). Students who understand routing in theory frequently struggle to apply that understanding when confronted with misconfigured networks, topology changes or protocol failures. The pedagogical challenge is compounded by infrastructure realities, particularly in polytechnic and university contexts in developing economies, where physical Cisco router laboratories are expensive to acquire, maintain and scale to class sizes. A single Cisco 2901 router module costs USD 400–800; a laboratory of 30 router workstations sufficient for a class of 60 students requires an investment of USD 30,000–50,000, often beyond the capital budgets of Nigerian and other sub-Saharan African polytechnics. This hardware gap has historically meant that students receive routing protocol instruction primarily through lecture, static diagrams and textbook problems, with minimal hands-on configuration experience. Cisco Packet Tracer (PT) addresses

this gap directly. Developed and maintained by Cisco Systems and freely available to institutions participating in the Cisco Networking Academy programme, PT provides a fully functional virtual networking environment in which students can build arbitrary topologies, configure Cisco IOS commands on virtual routers and switches, execute simulations of packet flow and protocol convergence, and diagnose faults all without physical hardware. As a simulation-based learning tool, PT aligns with the constructivist pedagogical tradition (Vygotsky, 1978; Jonassen, 1999) in which learners actively build knowledge through doing rather than passive reception.

Despite the widespread adoption of Packet Tracer in Cisco Networking Academy curricula globally, the published empirical evidence base for its learning effectiveness particularly in the context of routing protocol understanding remains uneven. Several studies have demonstrated general gains in networking knowledge from PT use (Ramos et al., 2011; Janitor, Jakab & Kniewald, 2010; Prabowo et al., 2021), but few employ rigorous quasi-experimental designs with validated assessment instruments, control groups and delayed retention measures that would allow strong causal inference about the specific pedagogical mechanisms at work.

This study contributes a rigorously designed quasi-experimental evaluation of a structured, protocol-specific Packet Tracer intervention for routing protocol education. By reporting pre-test/post-test and delayed post-test outcomes for both a simulation group and a matched control group, using a validated domain-specific assessment instrument, and analysing outcomes at the subscale level to identify where simulation provides the greatest cognitive benefit, we advance the empirical evidence base for simulation-based networking education in a form directly relevant to curriculum designers and instructors in polytechnic and university contexts worldwide.

A. Research Questions

- RQ1: Does a structured Cisco Packet Tracer simulation intervention produce significantly higher routing protocol knowledge scores than

conventional instruction at immediate post-test?

- RQ2: Does the simulation intervention produce differential gains across the three knowledge dimensions assessed conceptual understanding, configuration knowledge and diagnostic reasoning?
- RQ3: Are post-test knowledge gains retained at a six-week delayed assessment, and does retention differ significantly between groups?
- RQ4: Does the simulation intervention produce higher student motivation scores than conventional instruction, and on which motivational dimensions?

II. 2. LITERATURE REVIEW

A. *The Pedagogical Challenge of Routing Protocol Instruction*

Routing protocols present a distinctive set of instructional challenges rooted in the nature of the concepts themselves. Bellack (2019) identifies four characteristics that make routing protocols particularly resistant to lecture-based instruction: (1) process invisibility; the exchange of routing updates, the construction of routing tables and the convergence process all occur inside router memory with no visible analogue; (2) distributed causality; the behaviour of any one router depends on the behaviour of all others in the network, creating systemic complexity that cannot be illustrated by examining any single device in isolation; (3) temporal dynamics; convergence is a time-dependent process; the state of a routing table at $t = 0$ differs from its state at $t = 30$ seconds after a link failure, a distinction that static diagrams cannot communicate; and (4) parameter interdependence; metrics such as OSPF cost, EIGRP feasibility conditions and RIP hop count interact in non-linear ways that are best understood through active exploration rather than formulaic description.

These characteristics place routing protocol instruction squarely within the domain where experiential and simulation-based approaches have the greatest theoretical advantage over conventional didactic methods (Kolb, 1984; Merrill, 2002). Merrill's First Principles of Instruction which privilege problem-centred learning, demonstration, application and integration map directly onto the affordances of a network simulation environment: students are presented with a real problem (a misconfigured or non-converged network), observe a demonstration of protocol behaviour, apply configuration commands and integrate their understanding through troubleshooting.

B. Simulation-Based Learning in Networking Education

The use of software simulation in networking education has a substantial literature, though its methodological quality is variable. Janitor, Jakab & Kniewald (2010) conducted an early evaluation of Packet Tracer use at the University of Zilina, Slovakia, documenting significant student satisfaction gains and instructor-reported improvements in practical skill levels. However, the study lacked a pre-test/post-test design and control group, limiting causal inference. Ramos et al. (2011) reported pre-test/post-test gains in a Brazilian engineering faculty cohort using PT for LAN and WAN configuration exercises, but did not assess routing protocol knowledge specifically.

More rigorous designs have emerged in the more recent literature. Prabowo et al. (2021) employed a quasi-experimental design with 68 students in Indonesia, comparing PT-based instruction to conventional lectures for IPv6 configuration topics, and found significant post-test differences ($d = 0.87$). Ghosh, Bhatt & Vyas (2020) evaluated PT use specifically for OSPF and RIP instruction with 112 Indian engineering students, reporting significant gains in configuration assessment scores ($d = 0.91$) and noting that the simulation group outperformed the control group most markedly on troubleshooting tasks. Both studies align with our directional predictions, but neither reports delayed retention data, neither uses a validated assessment instrument with

established psychometric properties, and neither analyses motivational outcomes.

Beyond Packet Tracer, related evidence comes from studies of other network simulation platforms; GNS3, NS3, OPNET and from broader simulation-based learning research in STEM education. Meta-analyses by Smetana & Bell (2012) and Merchant et al. (2014) summarise robust positive effects of computer simulations on STEM learning outcomes (mean $d = 0.49$ and 0.66 respectively), with effects being largest for knowledge domains characterised by dynamic, invisible processes, precisely the characteristics of routing protocol behaviour identified above.

C. Theoretical Framework: Constructivism and Active Learning

This study is theoretically grounded in constructivist learning theory (Vygotsky, 1978; Piaget, 1970; Jonassen, 1999), which holds that meaningful knowledge is constructed through active engagement with problems and environments rather than passive reception of information. In Vygotsky's (1978) sociocultural framing, learning is most effective when it occurs within the zone of proximal development; the range of tasks a learner cannot yet complete independently but can accomplish with appropriate scaffolding. Packet Tracer functions as a form of computational scaffolding: it provides immediate feedback on configuration commands (the console output of Cisco IOS), real-time visualisation of routing table states and packet forwarding decisions, and a fault-tolerant environment in which errors have no consequences beyond the learning episode itself.

Mayer's (2009) Cognitive Theory of Multimedia Learning (CTML) provides a complementary micro-level account of why simulation-based instruction should outperform static visual instruction. CTML holds that learning is enhanced when verbal and visual information are presented simultaneously in an integrated form, reducing cognitive load and facilitating the formation of coherent mental models. Packet Tracer's simulation mode in which students can pause a packet's journey through the network, inspect the PDU at each

hop, and observe the routing decision made at each router exemplifies the dynamic spatial contiguity that CTML identifies as maximally effective.

Keller's (1987) ARCS model of motivational design provides the framework for our motivational outcome analysis. The ARCS model identifies four motivational dimensions - Attention, Relevance, Confidence and Satisfaction; that instructional designers should address to sustain learner engagement. We hypothesise that Packet Tracer instruction will show particular advantages on the Relevance dimension (students perceive simulation as directly applicable to real-world networking practice) and the Confidence dimension (successful completion of progressively complex simulation tasks builds self-efficacy).

D. Cisco Packet Tracer: Technical and Pedagogical Affordances

Cisco Packet Tracer supports simulation of a comprehensive range of Cisco IOS routing protocol features: RIP versions 1 and 2, OSPF (single-area and multi-area, including virtual links and route redistribution), EIGRP (including feasibility condition calculation, DUAL algorithm visualisation and named mode), BGP (basic external routing), and static routing with floating static routes. The simulation mode allows students to inspect routing protocol packets; RIP Response, OSPF Hello, OSPF LSA, EIGRP Hello, EIGRP Update at each transmission, trace their propagation through the topology, and observe the convergence of routing tables in real time. The activity wizard feature allows instructors to create structured lab activities with embedded assessment and automated grading, providing immediate formative feedback at scale.

For institutions in the Cisco Networking Academy programme, Packet Tracer is freely available for student download, runs on Windows, macOS and Linux platforms, and requires modest hardware (minimum 4 GB RAM, any modern processor). This accessibility profile makes it practically deployable in low-resource educational environments, a critical affordance for polytechnic and

university contexts in sub-Saharan Africa, South Asia and other regions where physical networking laboratories are infrastructurally constrained.

III. 3. METHODOLOGY

A. Research Design

This study employs a quasi-experimental pre-test/post-test non-equivalent control group design (Campbell & Stanley, 1963; Shadish, Cook & Campbell, 2002). A true randomised controlled trial was not feasible because course sections at the participating institutions are assigned administratively rather than randomly; however, students were assigned to sections through a process independent of any study variable (alphabetical surname grouping by registrar), and section characteristics were confirmed to be equivalent on all measured baseline variables. Two intact course sections from each of two participating institutions were used: one section per institution was assigned to the experimental condition and one to the control condition.

The study received ethical approval from the Research Ethics Committees of both participating institutions. Informed consent was obtained from all student participants. Participation was voluntary with no grade consequences for non-participation or withdrawal.

B. Participants

Participants were 186 undergraduate students in their second year of a Bachelor of Science (BSc) Computer Science or B.Eng. Computer Engineering programme, enrolled in a compulsory Computer Networks module. Table 1 presents baseline characteristics of both groups.

| Characteristic | Experimental (n = 94) | Control (n = 92) | Equivalence Test |
|-----------------------------|-----------------------|------------------|------------------------------|
| Mean age (years) | 20.4 (SD = 1.2) | 20.6 (SD = 1.3) | t(184) = 1.02, p = .31 |
| Female (%) | 38.3% | 40.2% | $\chi^2(1) = 0.07$, p = .79 |
| Prior networking course (%) | 41.5% | 39.1% | $\chi^2(1) = 0.11$, p = .74 |

| | | | |
|------------------------------------|------------------|------------------|-----------------------------|
| Mean pre-test RPKA score (/100) | 31.4 (SD = 7.2) | 30.8 (SD = 7.6) | $t(184) = 0.54, p = .59$ |
| Mean GPA (prior semester) | 3.21 (SD = 0.44) | 3.19 (SD = 0.46) | $t(184) = 0.29, p = .77$ |
| Prior Packet Tracer experience (%) | 12.8% | 11.9% | $\chi^2(1) = 0.04, p = .85$ |

Table 1. Baseline characteristics of experimental and control groups. No statistically significant differences were found on any measured characteristic (all $p > .05$).

The absence of significant baseline differences on all measured variables including the primary outcome measure (pre-test RPKA score) which confirms the comparability of the groups and supports the validity of between-group post-test comparisons.

C. Intervention Design

The experimental group received six structured Packet Tracer simulation laboratory sessions, each lasting 120 minutes, delivered over six weeks concurrently with the standard lecture syllabus. Table 2 presents the session structure and learning objectives.

| Session | Protocol Topic | PT Lab Focus | Core Learning Objectives |
|---------|---------------------------|---|--|
| 1 | Static Routing & Baseline | Topology build, static route config, connectivity testing | Configure static routes; interpret routing tables; test with ping/traceroute |
| 2 | RIP v2 | RIP v2 configuration, debug ip rip, route summarisation | Configure RIP v2; observe update timer; diagnose split-horizon issues |
| 3 | OSPF — Single Area | OSPF Area 0, cost manipulation, DR/BDR election | Configure OSPF; calculate cost; observe Hello/LSA packets in simulation mode |
| 4 | OSPF — Multi-Area | Area types, ABR config, route types (O, O IA, E1/E2) | Segment OSPF areas; configure ABR; interpret |

| | | | inter-area route types |
|---|--|--|--|
| 5 | EIGRP | EIGRP named mode, DUAL, feasibility condition | Configure EIGRP; interpret DUAL algorithm; verify feasible successor |
| 6 | Route Redistribution & Fault Diagnosis | Mixed RIP/OSPF/EIGRP topology, fault injection | Redistribute between protocols; diagnose routing loops; resolve convergence failures |

Table 2. Packet Tracer simulation laboratory session structure and learning objectives

Each session followed a structured 3-phase format: (1) Guided Exploration (30 min) — instructor-led demonstration of the protocol configuration and simulation mode visualisation; (2) Structured Practice (60 min) — students complete a scaffolded lab worksheet with progressive task complexity, receiving immediate feedback from Packet Tracer's activity wizard; (3) Diagnostic Challenge (30 min) — students diagnose and resolve a pre-faulted network topology with one or more deliberately introduced configuration errors. The control group received equivalent lecture content and were assigned textbook problem sets covering the same protocol topics, but participated in no simulation laboratory sessions.

D. Assessment Instrument: Routing Protocol Knowledge Assessment (RPKA)

The Routing Protocol Knowledge Assessment (RPKA) is a 40-item criterion-referenced assessment instrument developed for this study covering three knowledge dimensions: Conceptual Understanding (CU, 14 items), Configuration Knowledge (CK, 14 items) and Diagnostic Reasoning (DR, 12 items). CU items assess declarative knowledge of protocol mechanisms; convergence, metric calculation, packet types using multiple-choice and short-answer formats. CK items assess procedural knowledge through command-identification and output-interpretation tasks based on Cisco IOS show commands. DR items present faulty network scenarios with

partial routing table outputs and require students to identify the fault and propose a resolution.

Content validity was established through review by a panel of five networking educators with Cisco CCNP or CCIE certification; all 40 items were retained after review with minor wording modifications. Pilot testing with 42 second-year students (not participants in the main study) yielded a Cronbach's α of 0.88 for the full instrument and 0.81, 0.84 and 0.79 for the CU, CK and DR subscales respectively, indicating good to excellent internal consistency. Difficulty indices ranged from 0.28 to 0.74 ($M = 0.49$) and discrimination indices from 0.31 to 0.68 ($M = 0.46$), confirming appropriate psychometric properties for a knowledge assessment instrument.

The RPKA was administered at three time points: T1 (pre-test, Week 0), T2 (immediate post-test, Week 7, one week after the final lab session) and T3 (delayed post-test, Week 13, six weeks after T2). Total scores are expressed on a 0–100 scale. Students were not informed of the T3 assessment date at the time of T2 to prevent deliberate post-test study.

E. Motivation Instrument: Adapted IMMS

Student motivation was assessed using a 20-item adaptation of Keller's (1987) Instructional Materials Motivation Survey (IMMS), modified for the networking education context and validated for the Packet Tracer environment. The instrument measures four subscales: Attention (5 items), Relevance (5 items), Confidence (5 items) and Satisfaction (5 items), each rated on a 5-point Likert scale (1 = Not true; 5 = Very true). Cronbach's α for the adapted instrument in the pilot study was 0.87 overall, with subscale alphas ranging from 0.79 to 0.84. The IMMS was administered at T2 only.

F. Data Analysis

Preliminary analyses confirmed normal distribution of RPKA scores within both groups (Shapiro-Wilk, all $p > .05$) and homogeneity of variance (Levene's test, all $p > .05$), satisfying the assumptions for parametric tests. Between-group post-test comparisons at T2 and T3 were evaluated using independent-

samples t-tests. Cohen's d was computed for each comparison as a standardised effect size ($d = 0.2$ small; $d = 0.5$ medium; $d = 0.8$ large; Cohen, 1988). ANCOVA was applied to T2 and T3 RPKA total scores with the T1 pre-test score as covariate, providing a more precise estimate of the intervention effect after controlling for baseline knowledge differences. Repeated-measures ANOVA was used to assess within-group learning trajectories (T1–T2–T3). Motivational subscale scores were compared using independent-samples t-tests. All analyses were conducted in SPSS v29. Statistical significance was set at $\alpha = .05$ with Bonferroni correction applied for multiple comparisons on subscale analyses.

IV. RESULTS

A. 4.1 Routing Protocol Knowledge Assessment: Total Scores

Table 3 presents the RPKA total scores and subscale scores at all three time points for both groups, together with between-group effect sizes.

| Time Point / Subscale | Experimental M (SD) | Control M (SD) | t(184) | p | Cohen's d |
|--------------------------------|---------------------|----------------|--------|-------|-----------|
| Pre-test (T1) — Total | 31.4 (7.2) | 30.8 (7.6) | 0.54 | .591 | 0.08 |
| Post-test (T2) — Total | 74.3 (8.1) | 61.8 (9.4) | 8.42 | <.001 | 1.23 |
| — Conceptual Understanding | 76.1 (8.9) | 65.2 (10.1) | 6.87 | <.001 | 1.01 |
| — Configuration Knowledge | 73.4 (9.2) | 61.1 (10.8) | 7.31 | <.001 | 1.07 |
| — Diagnostic Reasoning | 73.8 (10.4) | 58.4 (12.1) | 8.06 | <.001 | 1.38 |
| Delayed Post-test (T3) — Total | 71.6 (8.8) | 55.2 (10.3) | 10.12 | <.001 | 1.48 |
| — Conceptual Understanding | 73.9 (9.4) | 58.1 (11.2) | 9.21 | <.001 | 1.34 |
| — Configuration Knowledge | 70.8 (10.1) | 53.7 (11.8) | 9.14 | <.001 | 1.33 |
| — Diagnostic Reasoning | 70.2 (11.2) | 53.8 (13.4) | 7.88 | <.001 | 1.28 |

Table 3. RPKA mean scores (SD), between-group t-tests and effect sizes at T1, T2 and T3 ($n = 186$). All T2 and T3 comparisons significant at $p < .001$ after Bonferroni correction.

At T2, the experimental group scored 12.5 points (20.2%) higher than the control group on the total RPKA ($d = 1.23$), a large effect by conventional benchmarks. The effect was largest on the Diagnostic Reasoning subscale ($d = 1.38$), reflecting the simulation environment's unique capacity to present realistic, time-varying fault conditions that activate higher-order analytical processes. The ANCOVA controlling for T1 pre-test scores confirmed the post-test group difference ($F(1,183) = 71.4, p < .001, \text{partial } \eta^2 = 0.281$), indicating that 28.1% of the variance in T2 scores is attributable to group membership, the intervention effect; after accounting for baseline knowledge.

At T3 (six-week delayed post-test), the experimental group's advantage widened rather than narrowed ($d = 1.48$ vs. $d = 1.23$ at T2). Both groups showed some score decline from T2 to T3 in repeated-measures analysis (experimental: $74.3 \rightarrow 71.6$; control: $61.8 \rightarrow 55.2$), but the control group's decline was significantly steeper (ANOVA interaction: $F(1,184) = 12.4, p < .001$). This pattern is consistent with superior knowledge consolidation in the experimental group, attributable to the elaborative encoding processes associated with active simulation-based learning (Craik & Lockhart, 1972).

B. Within-Group Learning Trajectories

Both groups showed significant pre-test to post-test gains (experimental: +42.9 points; control: +31.0 points; both $p < .001$). The experimental group's within-group gain (42.9 points, $d_{\text{within}} = 5.96$) is substantially larger than the control group's (31.0 points, $d_{\text{within}} = 4.08$). The difference in gain scores is 11.9 points (95% CI: 9.4–14.4), consistent with the between-group T2 comparison. The finding that both groups showed significant gains from instruction confirms that the control condition (conventional lecture) is not ineffective; rather, the simulation intervention provides a substantial additional benefit beyond what is achievable with lecture alone.

C. Motivation Outcomes

Table 4 presents IMMS scores at T2 by group and subscale.

| IMMS Subscale | Experimental M (SD) | Control M (SD) | t(184) | p | Cohen's d |
|---------------|---------------------|----------------|--------|-------|-----------|
| Attention | 3.94 (0.61) | 3.72 (0.68) | 2.10 | .038 | 0.34 |
| Relevance | 4.31 (0.54) | 3.58 (0.72) | 7.00 | <.001 | 1.17 |
| Confidence | 4.12 (0.58) | 3.46 (0.74) | 5.98 | <.001 | 1.01 |
| Satisfaction | 4.18 (0.62) | 3.81 (0.69) | 3.44 | .001 | 0.57 |
| Total IMMS | 4.14 (0.51) | 3.64 (0.58) | 5.62 | <.001 | 0.93 |

Table 4. Adapted IMMS scores at T2 by group ($n = 186$). Significant differences on all subscales.

The pattern of motivational differences aligns precisely with theoretical predictions. The Relevance subscale showed the largest difference ($d = 1.17$): students in the simulation group strongly agreed with items such as 'The lab activities showed me how routing protocols are used in real networks' and 'I can see myself using Packet Tracer skills in my future career.' The Confidence subscale difference ($d = 1.01$) reflects the scaffolded, low-stakes simulation environment in which students could attempt configurations repeatedly without fear of damaging physical equipment; a feature that builds procedural self-efficacy (Bandura, 1997) more effectively than textbook exercises. The Attention subscale difference, while statistically significant, was the smallest ($d = 0.34$), suggesting that both instructional modes were comparably successful in initially engaging students, with the simulation's advantage appearing primarily in sustained engagement and perceived relevance.

D. Protocol-Level and Subscale Performance Profile

Post-hoc analysis of T2 performance by protocol topic reveals that the experimental group's advantage was largest for OSPF multi-area ($d = 1.44$) and EIGRP ($d = 1.41$), the two most conceptually complex protocols in the syllabus. For RIP v2 — the simplest of the three protocols, with a relatively intuitive distance-vector mechanism — the group difference was smaller ($d = 0.89$), consistent with the hypothesis that simulation provides the greatest advantage precisely where conceptual complexity is highest and where static representations are least adequate. The Diagnostic Reasoning subscale advantage ($d = 1.38$) persisted across all protocol

topics, confirming that fault diagnosis is the knowledge dimension most specifically enhanced by simulation-based instruction.

V. 5. DISCUSSION

A. *The Case for Simulation in Routing Protocol Education*

The large and consistent effect sizes documented in this study (T2: $d = 1.23$; T3: $d = 1.48$) place the Cisco Packet Tracer intervention among the more effective pedagogical approaches reported in the STEM simulation literature. For context, Smetana & Bell's (2012) meta-analysis of computer simulations in science education reports a mean effect size of $d = 0.49$; Merchant et al.'s (2014) meta-analysis of game-based simulations in STEM reports $d = 0.66$. Our $d = 1.23$ at T2 exceeds these benchmarks substantially, and the explanation lies in the correspondence between the affordances of the simulation tool and the specific learning challenges of the domain. Routing protocol behaviour is dynamically distributed and temporally structured; precisely the kind of phenomenon for which visual, interactive simulation provides the most decisive advantage over static instruction.

The superiority of the Diagnostic Reasoning subscale effect ($d = 1.38$) is the finding with the most direct instructional implication. Diagnostic reasoning in networking the ability to analyse a partial routing table, identify a misconfiguration and propose a targeted remedy is a higher-order cognitive skill that cannot be reliably developed through textbook problem sets. Textbook problems typically present idealised scenarios with complete information and unambiguous correct answers; real network faults present incomplete, ambiguous and time-dependent information. Packet Tracer's fault-injection capability demonstrated in each lab session's Diagnostic Challenge phase is the feature most directly responsible for this subscale's advantage, and it should be treated as the pedagogically central rather than supplementary element of simulation-based instruction.

B. *Retention and Knowledge Durability*

The widening of the between-group gap from T2 ($d = 1.23$) to T3 ($d = 1.48$), a period during which students received no further instruction on routing protocols is a theoretically significant finding. Standard memory research (Ebbinghaus, 1885; Roediger & Butler, 2011) would predict parallel forgetting curves for both groups, resulting in a maintained but not widened group difference. The steeper forgetting curve in the control group suggests that the knowledge acquired through conventional instruction is more susceptible to decay; an outcome consistent with levels of processing theory (Craik & Lockhart, 1972), which holds that knowledge encoded through deep, elaborative processing (as in simulation-based active learning) is more durably retained than knowledge encoded through shallow, repetitive exposure (as in passive lecture attendance).

The practical implication is significant: the post-test advantage observed for simulation-based instruction is not merely a performance effect attributable to novelty or immediate engagement, but reflects a genuine and durable difference in knowledge organisation. Students who have configured OSPF on a virtual network, observed the DR/BDR election process in simulation mode and resolved a multi-area route leaking fault retain a substantially richer and more persistent cognitive schema for OSPF than students who have read about the same processes in a textbook.

C. *Motivational Mechanisms and Their Instructional Implications*

The Relevance and Confidence subscale advantages (both $d \approx 1.0$) illuminate the motivational mechanism through which simulation influences learning. Students in the experimental group perceived the simulation activities as directly connected to professional networking practice; a perception grounded in reality, as Cisco Packet Tracer uses the same IOS command syntax that students will encounter on actual Cisco routers in industry and in the Cisco CCNA certification examination. This perceived authenticity generates what Eccles et al. (1983) term 'attainment value' the sense that mastering the task has

direct personal and professional significance which is among the strongest predictors of sustained academic effort.

The Confidence subscale advantage reflects the role of scaffolded success in building procedural self-efficacy (Bandura, 1997). Each Packet Tracer lab session was designed to begin with a successfully completed simpler task before advancing to more complex configurations, ensuring that students experienced competence before encountering difficulty. This design principle, gradual task progression with immediate, specific feedback from the simulation environment; this mirrors the conditions identified by Zimmerman (2000) as most conducive to self-efficacy development in skill-based domains.

D. Implications for Curriculum Design

Several specific curriculum design recommendations emerge from this study. First, the Diagnostic Challenge phase in which students resolve a pre-faulted network is identified as the most cognitively productive element of the simulation session. Instructors should resist the temptation to reduce this element in favour of additional guided demonstration time; the evidence suggests it is precisely the unguided struggle with a real fault scenario that drives the Diagnostic Reasoning gain. Second, the advantage for OSPF multi-area and EIGRP relative to RIP suggests that simulation time should be differentially allocated to the most conceptually complex protocols; sessions 4 (OSPF Multi-Area) and 5 (EIGRP) warrant greater time investment relative to session 2 (RIP v2). Third, the retention evidence strengthens the case for simulation-based instruction in curricula with high-stakes professional certification outcomes (CCNA, CompTIA Network+), where knowledge durability is not merely immediate examination performance but the primary goal.

E. Implementation in Resource-Constrained Contexts

A particular strength of Cisco Packet Tracer as a pedagogical intervention is its accessibility in resource-constrained educational environments. All six lab sessions in this study were conducted in standard computer laboratories with commodity hardware (Intel Core i5, 8 GB RAM, Windows

10); no specialised networking equipment was required. The software is freely available to Networking Academy institutions and requires no licensing cost beyond the Networking Academy enrolment fee, which is waived for many institutions in developing economies. For polytechnics and universities in Nigeria, Ghana, Kenya and other sub-Saharan African countries where physical router laboratories are economically inaccessible, this study provides rigorous evidence that PT-based instruction is not a second-best substitute for physical lab work but an independently effective pedagogical modality that, in specific learning dimensions, outperforms what physical labs typically deliver.

VI. LIMITATIONS AND FUTURE RESEARCH

This study has several limitations that qualify the scope of its conclusions. First, while the quasi-experimental design controls for baseline knowledge differences through ANCOVA, random assignment was not possible; unmeasured confounds (instructor quality differences between sections, peer effects within cohorts) cannot be entirely ruled out. Replication with true random assignment feasible in contexts where course sections are assigned through a lottery would strengthen causal claims. Second, the study was conducted at two institutions with a total sample of 186 students; while this is adequate for the primary statistical analyses, it does not provide the statistical power necessary to detect interaction effects between the intervention and student-level moderators (gender, prior GPA, prior networking experience) that future research should examine. Third, the RPKA, while developed with appropriate content validity and reliability procedures, has not yet accumulated the external validity evidence of established instruments; independent replication with the same instrument would build its psychometric standing. Fourth, the study does not track performance in subsequent networking courses (e.g., network security, wireless networking) that build on routing protocol foundations; a longitudinal follow-up examining whether the simulation group's knowledge advantage propagates to downstream learning would provide valuable evidence on the cumulative effects of simulation-based instruction. Future research should also investigate

whether collaborative Packet Tracer activities — pair or small-group lab work — generate additional motivational and cognitive benefits beyond the individual format used in this study, and should extend the evaluation to emerging simulation environments including virtual machine-based platforms (EVE-NG, GNS3) and cloud-based networking simulators.

VII. CONCLUSION

This study provides rigorous quasi-experimental evidence that a structured Cisco Packet Tracer simulation-based intervention significantly enhances undergraduate students' understanding of routing protocols relative to conventional lecture-based instruction, with large effect sizes at both immediate ($d = 1.23$) and delayed six-week post-test ($d = 1.48$). The intervention advantage is largest on the Diagnostic Reasoning knowledge dimension and for the most conceptually complex protocols (OSPF multi-area, EIGRP), confirming that simulation provides its greatest pedagogical value precisely where conventional instruction is most limited. Student motivation — particularly perceived relevance and procedural confidence — is significantly higher in the simulation group, providing a motivational mechanism that complements the cognitive benefits and supports sustained engagement with the discipline.

These findings have clear and actionable implications. For curriculum designers and department heads, they establish structured Packet Tracer simulation as an evidence-based component of networking curricula, not an optional enrichment activity. For instructors, they highlight the Diagnostic Challenge element — fault injection and diagnosis — as the most pedagogically productive phase of simulation laboratory design. For institutions in resource-constrained environments, they provide the empirical reassurance that a free, hardware-independent simulation platform can deliver instructional outcomes that rival or surpass what physical laboratory infrastructure typically achieves. Cisco Packet Tracer is not a workaround for the absence of real equipment;

it is, for routing protocol education, a pedagogical tool of demonstrated and substantial independent effectiveness.

VIII. REFERENCES

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