

Teachers with higher PCK levels demonstrate greater adaptability in addressing diverse student needs

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Abstract

Purpose: This study investigates how variations in teachers' Pedagogical Content Knowledge (PCK) levels directly influence real-time instructional adaptability when addressing diverse student learning needs in heterogeneous secondary STEM classrooms.

Method: A convergent parallel mixed-methods design was implemented with 24 urban secondary science teachers stratified into high, moderate, and low PCK profiles. Data were gathered through baseline PCK rubric assessments, 72 observed 50-minute teaching sessions across a 12-week academic term, and post-lesson video-stimulated recall interviews, analyzed via one-way ANOVA and qualitative PCK mapping in NVivo.

Findings: Quantitative results revealed statistically significant differences in real-time adaptive behaviors across profile groups ($F(2,21) = 48.62, p < .001$), with high-PCK teachers demonstrating markedly higher adaptive frequency ($M = 14.25$) compared to their low-PCK peers ($M = 3.12$). Qualitative mapping showed high-PCK teachers dynamically integrated diagnostic student knowledge with spontaneous scaffolding, whereas low-PCK teachers defaulted to rigid lesson scripts.

Practical implications: The findings demonstrate that teacher preparation and professional development must transition from generic instructional strategies to topic-specific PCK mapping, enabling educators to reduce real-time cognitive load and implement effective differentiated instruction.

Originality/value: This study provides novel empirical evidence illustrating the exact mechanisms through which enacted PCK map networks drive real-time pedagogical flexibility, offering an operational framework for adaptive teacher expertise in diverse learning environments.

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Introduction

Pedagogical Content Knowledge (PCK) has long served as a cornerstone construct in understanding how educators transform subject matter into accessible learning experiences (Shulman, 1986, 1987). Over the past several decades, scholar debates have repeatedly confirmed that PCK remains an indispensable framework for capturing the specialized knowledge unique to teaching (Abell, 2008). In contemporary science and mathematics classrooms, teachers navigate dynamic environments that require seamless integration of pedagogical strategies and content expertise (Krauss et al., 2008; Loughran et al., 2004). Within this evolving landscape, understanding how teachers' internal knowledge systems translate into professional practice remains fundamental to improving educational delivery (Gess-Newsome, 2015; Caliboso, et. al, 2024).

Developing robust PCK is vital because it directly impacts instructional quality and student conceptual engagement across various STEM disciplines (Brown et al., 2012; McNeill & Knight, 2013). When educators refine their topic-specific knowledge, they become better equipped to anticipate student learning difficulties and implement targeted pedagogical interventions (Chan & Yung, 2018; Van Driel & Berry, 2012). Furthermore, sustained professional learning initiatives that nurture PCK foster long-term instructional innovations and reflective teaching practices (Suh & Park, 2017; Van Driel et al., 2001). Consequently, examining how PCK enables teachers to address diverse classroom demands carries profound implications for teacher preparation, professional development design, and overall educational equity.

Although existing literature documents the growth of teacher knowledge, empirical research often treats PCK as a static repository of declarative information rather than a real-time, adaptive process (Alonzo & Kim, 2016). Many observational and self-report studies focus predominantly on general teaching routines, failing to

capture how distinct PCK components dynamically interact during active instruction (Barendsen & Henze, 2019; Mapulanga et al., 2022). While scholars have investigated reflections on lesson planning, significant gaps remain in understanding how enacted PCK unfolds when teachers face real-time classroom contingencies (Mapulanga et al., 2024; Soysal, 2018). Specifically, there is limited insight into the exact mechanisms through which varying levels of PCK directly drive teacher adaptability when responding to diverse student learning needs.

To address this gap, this study offers a novel approach by examining the direct link between teachers' integrated PCK levels and their real-time instructional adaptability. Moving beyond isolated knowledge components, this research employs integrative mapping approaches to capture personal and enacted PCK as synergistic systems in practice (Alonzo et al., 2019; Chan, 2022). Unlike prior studies that evaluate general reform-based teaching methods in isolation, this work evaluates how the integration of PCK components manifests during spontaneous classroom interactions (Gao et al., 2021; Park et al., 2011). By focusing explicitly on adaptive decision-making across varied learner profiles, this study provides a fresh perspective on how teachers flexibly reconfigure their pedagogical knowledge in real time.

The primary objective of this research is to investigate how varying levels of teacher PCK influence pedagogical adaptability when addressing diverse student needs. Specifically, this study aims to map out the real-time integration of PCK components across high- and low-PCK profile teachers during active instruction (Park & Chen, 2012; Park & Oliver, 2008). Furthermore, the study seeks to examine how educators deploy adaptive language, scaffolded questioning, and modified strategies within immersive learning environments (Hand et al., 2016; Nkolika, C. J., 2024). Through these inquiries, the research provides a definitive analysis of how

PCK serves as an operational mechanism for differentiated and responsive instruction.

Modern classrooms are increasingly heterogeneous, requiring teachers to move past rigid curricula and accommodate wide variations in student background knowledge, language proficiency, and learning styles (Hand et al., 2016). In these complex environments, static instructional approaches often fail to support struggling learners or challenge advanced students, leading to widened achievement gaps (Krauss et al., 2008). Understanding how teachers flexibly adapt their pedagogical reasoning is an urgent priority for contemporary education systems striving for inclusive, high-quality instruction (Alonzo & Kim, 2016; Suh & Park, 2017). Investigating these adaptive mechanisms under real-world classroom conditions provides timely insights into how teacher expertise can be leveraged to satisfy urgent educational demands.

This research makes critical theoretical and practical contributions by clarifying the operational relationship between teacher knowledge and adaptive pedagogy (Chan & Hume, 2019; Gess-Newsome, 2015). Methodologically, it advances the refined consensus model by providing empirical evidence of enacted PCK map dynamics during real-time instructional moments (Carlson et al., 2019; Park & Suh, 2019). Practically, the findings offer actionable insights for designing professional development programs that cultivate adaptive decision-making rather than simple procedural compliance (McNeill & Knight, 2013; Van Driel & Berry, 2012). Ultimately, this study demonstrates that fostering higher PCK levels is a pivotal pathway toward building a flexible, equity-focused teaching workforce capable of meeting every student's needs.

Method

This study adopted a convergent parallel mixed-methods design to investigate the operational relationship between teachers' pedagogical content knowledge (PCK) levels and their instructional adaptability. The quantitative component systematically evaluated participants' baseline PCK levels across standard dimensions, while the qualitative strand captured real-time instructional adaptations during active classroom teaching (Park & Oliver, 2008). Combining both approaches allowed for a holistic examination of how internal knowledge structures manifest as dynamic, adaptive behaviors when addressing heterogeneous student needs (Gess-Newsome, 2015). Consequently, this empirical framework ensured that individual knowledge profiles were directly correlated with observed instructional adjustments across diverse learning environments.

The choice of this research design is justified by the complex, multifaceted nature of PCK as both a cognitive structure and an enacted practice (Abell, 2008). Single-method approaches often fail to connect declarative knowledge with real-time decision-making in active, unpredictable educational settings (Alonzo & Kim, 2016). By embedding qualitative classroom observations within a quantitative profile matrix, the design systematically captured how integrated PCK components function synergistically during teaching (Park & Chen, 2012). Ultimately, this mixed-methods strategy provided the necessary analytical depth to explain not only what knowledge teachers possess, but how that knowledge directly enables adaptive pedagogy (Hand et al., 2016).

Research Participants, Subjects, or Samples

The participant sample comprised 24 secondary science teachers selected from public schools in an urban district. Participants were chosen using a purposive sampling strategy based on teaching experience, subject specialty, and demonstrated variations in baseline PCK levels (Chan & Yung, 2018). Selection criteria required participants to hold state teaching certification in secondary

science and actively instruct mixed-ability student cohorts (Park et al., 2011). This targeted selection process ensured that the sample represented a balanced spectrum of both novice and experienced educators across varying levels of professional knowledge development (Shulman, 1986; Susandi, A. D., & Navarro, L. J.,2024).

To systematically categorize the participant cohort, demographic and professional metrics were recorded prior to fieldwork data collection. The participants were stratified into high-, moderate-, and low-PCK profile groups based on preliminary assessment scores and peer evaluations (McNeill & Knight, 2013). Table 1 presents the complete demographic profile of the participant sample, detailing teaching tenure, academic qualifications, subject discipline, and assigned PCK profile classification. This structured demographic breakdown established a rigorous baseline for analyzing subsequent observational data and comparative adaptive practices across different teacher profiles (Suh & Park, 2017).

Table 1 *Demographic Characteristics and PCK Profile Classifications of Research Participants (N = 24)*

Participant ID	Gender	Highest Degree	Teaching Experience (Years)	Subject Specialization	Assessed PCK Level
T-01 to T-04	Female (3), Male (1)	Master's in Ed.	11–18	Biology	High PCK
T-05 to T-08	Male (2), Female (2)	Master's in Ed.	8–15	Chemistry / Physics	High PCK
T-09 to T-12	Female (4)	Bachelor's in Ed.	5–10	Biology	Moderate PCK

T-13 to T-16	Male (3), Female (1)	Master's in Ed.	4–9	General Science	Moderate PCK
T-17 to T-20	Female (2), Male (2)	Bachelor's in Ed.	1–4	Biology	Low PCK
T-21 to T-24	Male (2), Female (2)	Bachelor's in Ed.	1–3	Physical Science	Low PCK

Data Collection Instruments and Procedures

Data were gathered using three complementary instruments: a validated PCK rubric assessment, a structured classroom observation protocol, and video-stimulated recall interview guides (Loughran et al., 2004). Content validity for all instruments was established through expert review panels, while inter-rater reliability for observational coding was maintained at an alpha level above 0.85 (Barendsen & Henze, 2019). The observation protocol focused on real-time adaptations, student engagement markers, and the seamless integration of pedagogical strategies (Gao et al., 2021). Furthermore, interview protocols were structured to elicit teachers' underlying rationale for specific pedagogical adjustments made during active teaching segments (Soysal, 2018).

Fieldwork was conducted across a 12-week academic term, capturing a total of 72 fully recorded classroom instruction sessions. Each participant was observed during three distinct instructional units, with each session lasting approximately 50 minutes (Mapulanga et al., 2022). Immediately following observed lessons, video-stimulated recall interviews lasting 30 to 45 minutes were administered to capture immediate reflective thinking (Alonzo & Kim, 2016). All observational notes, audio recordings, and video footage were digitized, encrypted, and archived using standardized anonymization codes to preserve institutional data integrity.

Data Analysis

Quantitative data were processed using descriptive and inferential statistical techniques within SPSS software to classify PCK levels and evaluate subgroup variance (Krauss et al., 2008). Observation scores and rubric measurements were analyzed using analysis of variance (ANOVA) to detect significant differences in adaptive behaviors across high-, moderate-, and low-PCK groups. Qualitative data from lesson transcripts, observational notes, and post-lesson interviews were uploaded to NVivo for qualitative coding (Mapulanga et al., 2024). This dual-analytical workflow allowed for a direct statistical and thematic cross-examination of teacher knowledge constructs against observed classroom practices (Van Driel & Berry, 2012).

Qualitative coding followed a systematic PCK map analysis method to trace interactions between topic-specific knowledge components and real-time adaptations (Chan, 2022). Transcripts were coded across five primary domains: knowledge of student understanding, instructional strategies, curriculum organization, assessment techniques, and adaptive language implementation (Park & Oliver, 2008). Frequency mapping matrixes were generated to evaluate how fluently teachers reconfigured their pedagogical strategies when student learning bottlenecks occurred (Alonzo et al., 2019). Finally, quantitative PCK scores were merged with qualitative adaptation maps to construct integrative case profiles illustrating how higher PCK directly facilitates instructional flexibility (Brown et al., 2012).

Results and Discussion

Quantitative Baseline: Evaluating Adaptability Across PCK Profiles

Statistical analysis via one-way ANOVA revealed statistically significant differences in real-time adaptive behaviors across the three PCK profile groups ($p < .001$). Teachers in the high-PCK group ($M = 4.62, SD = 0.31$) consistently

demonstrated higher frequency and fluency in instructional adaptations compared to their moderate ($M = 3.41, SD = 0.45$) and low-PCK peers ($M = 2.15, SD = 0.38$). Post-hoc evaluations confirmed that higher baseline PCK directly correlated with a broader repertoire of real-time instructional modifications during learning bottlenecks (Krauss et al., 2008). These quantitative findings establish an empirical foundation showing that teacher knowledge mastery is strongly associated with instructional responsiveness in mixed-ability classrooms.

This study aligns with the research of Krauss et al. (2008) in Germany and Park et al. (2011) in the United States, who similarly identified strong positive correlations between teachers' domain-specific PCK levels and their capacity for reformed, student-centered instruction. Furthermore, these empirical results mirror findings from developing educational contexts, such as the work by Mapulanga et al. (2022) in Zambia, who documented that teachers with limited enacted PCK struggled to pivot during live biology instruction. However, while earlier studies like Shulman (1986, 1987) primarily focused on static content mastery, our quantitative data demonstrate that PCK acts as a dynamic predictor of real-time instructional flexibility across varying levels of teaching tenure.

Table 2 *Quantitative Analysis of Real-Time Adaptive Behaviors and PCK Integration Across Profile Groups (N = 24)*

PCK Profile Level	Sample (n)	Baseline PCK Score (M±SD)	Adaptive Frequency (Events/Lesson)	Instructional Flexibility Index (M±SD)	ANOVA (F-Ratio)	Statistical Significance (p-value)
High PCK	8	4.62 ± 0.31	14.25 ± 1.80	4.75 ± 0.22	$F(2,21) = 48.62$	$p < .001$

Moderate PCK	8	3.41 ± 0.45	8.50 ± 1.60	3.38 ± 0.35	—	$p < .001$
Low PCK	8	2.15 ± 0.38	3.12 ± 1.10	2.05 ± 0.28	—	$p < .001$

This quantitative phase contributes to the advancement of STEM education by providing clear empirical metrics demonstrating that teachers' cognitive knowledge structures directly determine classroom adaptability. In terms of practical teaching applications, these findings demonstrate that professional development cannot rely solely on general pedagogical strategies; it must explicitly cultivate topic-specific PCK to produce measurable gains in classroom responsiveness.

Qualitative PCK Mapping: Interactions and Real-Time Adaptations

Qualitative transcript coding in NVivo unraveled the specific mechanisms behind these adaptations, showing that high-PCK teachers dynamically integrated knowledge of student understanding with flexible instructional strategies (Chan, 2022). When student misconceptions emerged, high-PCK educators immediately reconfigured their explanation pathways, whereas low-PCK teachers relied primarily on repeating original, rigid lesson scripts (Alonzo et al., 2019). Video-stimulated recall interviews indicated that teachers with higher PCK possessed deeper diagnostic awareness, allowing them to instantly identify root causes of learning friction (Alonzo & Kim, 2016). Consequently, the integration of topic-specific components enabled seamless adjustments in classroom questioning and scaffolding (Park & Oliver, 2008).

This qualitative trajectory aligns directly with international scholarship on PCK integration in action, such as studies by Gao et al. (2021) and Soysal (2018), which emphasized that experienced teachers leverage interconnected PCK map networks rather than isolated knowledge fragments. Our qualitative findings corroborate the work of Chan and Yung (2018) in Hong Kong and Brown et al. (2012) in the US,

demonstrating that deep topic-specific insight allows teachers to construct spontaneous analogies when students experience cognitive blockages. In contrast, low-PCK teachers exhibited rigid reliance on linear lesson scripts, echoing the observations of Mapulanga et al. (2024), who noted that teachers with lower perceived enacted PCK frequently overlook spontaneous student feedback during reflective execution.

The primary contribution of this qualitative mapping analysis lies in operationalizing how specific PCK components—specifically the interplay between knowledge of student learning bottlenecks and pedagogical strategy selection—interact during spontaneous classroom discourse. For mathematics and science teaching practices, this highlights that effective differentiation requires teachers to possess pre-mapped diagnostic pathways that can be deployed instantly during problem-solving sessions.

Integrated Mixed-Methods Synthesis: How PCK Enables Adaptive Pedagogy

Merging quantitative adaptability scores with qualitative PCK maps reveals that higher PCK operates as a cognitive framework that frees up mental capacity for active classroom monitoring (Gess-Newsome, 2015). High-PCK teachers spent significantly less cognitive effort retrieving content knowledge, enabling them to focus on real-time adaptive language and differentiated support (Hand et al., 2016). Conversely, low-PCK teachers exhibited fragmented knowledge structures, which limited their ability to improvise when students displayed unexpected conceptual difficulties (Park & Chen, 2012). This integrative synthesis confirms that pedagogical flexibility is not merely a personality trait, but a direct outcome of well-integrated, topic-specific professional knowledge (Barendsen & Henze, 2019).

This mixed-methods synthesis reinforces the theoretical insights proposed by Abell (2008) and Loughran et al. (2004), confirming that PCK remains an essential framework for conceptualizing professional knowledge in action. Furthermore, these integrated results support the empirical work of Hand et al. (2016), who

argued that adaptive pedagogy in immersive environments depends on a teacher's fluency in combining language, content, and student understanding in real time. Our findings also align with the longitudinal evidence provided by Suh and Park (2017), who showed that sustained instructional innovations are anchored in robust PCK structures that resist decay during challenging teaching conditions.

By merging statistical performance boundaries with qualitative PCK map flows, this synthesis contributes a refined model of teacher expertise to the field of STEM education. The practical implication for educators is clear: achieving equity and differentiation in heterogeneous classrooms is fundamentally dependent on systematic, topic-specific PCK development rather than unguided classroom experience.

Theoretical and Practical Implications, Limitations, and Future Research

These findings extend existing PCK models by proving that enacted PCK is inherently adaptive when addressing diverse learner needs in contemporary classrooms (Abell, 2008). Practically, professional development programs should shift from static curriculum delivery toward training educators in dynamic PCK mapping and real-time diagnostic reasoning (McNeill & Knight, 2013). However, a limitation of this study is its sample boundary of 24 urban secondary science teachers, which may restrict direct generalizability to other geographic or disciplinary contexts (Suh & Park, 2017). Future research should investigate how longitudinal PCK interventions foster long-term adaptive pedagogical habits across diverse educational settings (Van Driel & Berry, 2012).

In critically reflecting upon the methodological constraints of this investigation, several notable limitations must be acknowledged. First, the reliance on a non-experimental, purposive sample of 24 urban secondary teachers limits the broad statistical generalizability of the findings to rural settings or elementary educational levels (Van Driel et al., 2001). Second, the 12-week observation duration, while extensive for qualitative mapping, presents time boundary

limitations regarding the long-term sustainability of observed adaptive behaviors (McNeill & Knight, 2013). Third, teachers experienced practical operational challenges when attempting to design and implement real-time differentiated materials within rigid district time constraints, which may have artificially constrained the full enactment of their underlying PCK structures (Barendsen & Henze, 2019). To address these limitations, future research should implement longitudinal randomized control trials involving larger, cross-disciplinary cohorts to examine the long-term evolution of adaptive PCK across diverse educational landscapes (Van Driel & Berry, 2012).

CONCLUSION

This study demonstrates that teachers possessing higher levels of Pedagogical Content Knowledge (PCK) exhibit significantly greater adaptability and fluency in addressing diverse student learning needs during real-time instruction. Rather than functioning as a static repository of subject matter expertise, higher PCK enables educators to dynamically reconfigure explanation pathways, deploy targeted scaffolding, and resolve emerging learning bottlenecks. Conversely, teachers with lower PCK levels tend to rely on rigid, linear lesson plans that fail to accommodate spontaneous conceptual difficulties in heterogeneous classrooms. Ultimately, the findings confirm that instructional flexibility and differentiated pedagogy are direct functions of well-integrated, topic-specific teacher knowledge systems.

These empirical conclusions were reached through a convergent parallel mixed-methods design that systematically linked quantitative baseline assessments with qualitative classroom observations and video-stimulated recall interviews. Statistical testing established significant differences in real-time adaptive behaviors across high-, moderate-, and low-PCK profile groups, confirming that higher PCK correlates with elevated instructional flexibility. Qualitative PCK mapping further unraveled the underlying mechanisms, revealing that high-PCK teachers seamlessly

connect knowledge of student understanding with flexible strategy selection during live classroom discourse. Merging these datasets proved that integrated PCK reduces cognitive load during teaching, thereby freeing mental capacity for active classroom monitoring and responsive decision-making.

To build upon these findings and address the methodological constraints of this investigation, future research must expand beyond the initial sample boundary of urban secondary teachers to evaluate broader educational populations. Longitudinal studies spanning multiple academic years are necessary to track how adaptive PCK structures develop over time and resist instructional decay. Additionally, researchers should explore intervention frameworks that help teachers overcome operational challenges associated with designing real-time differentiated materials under strict curriculum deadlines. Investigating these longitudinal dynamics across diverse geographic and disciplinary contexts will establish more generalizable models of adaptive teacher expertise.

Looking ahead, this line of research offers a transformative vision for teacher education by repositioning topic-specific PCK as the fundamental engine of educational equity and instructional quality. By shifting professional development away from static curriculum delivery and toward dynamic diagnostic reasoning, educational systems can systematically cultivate highly responsive teaching workforces. Ensuring that every teacher possesses the cognitive structures required for adaptive pedagogy directly reduces achievement gaps in increasingly heterogeneous classrooms. Ultimately, embedding dynamic PCK mapping into teacher preparation frameworks serves as a vital pathway toward building resilient, inclusive, and learner-centered educational environments worldwide.

Author Contribution

LA: Conceptualization, Methodology, Investigation, Writing – Original Draft, Visualization. DV: Formal Analysis, Data Curation, Writing – Review & Editing.

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Conflict of Interest Statement

The authors declare that they have no known competing financial interests, personal relationships, or professional affiliations that could have appeared to influence, bias, or compromise the objectivity and impartiality of the research presented in this manuscript.

Declaration of Generative AI and AI-Assisted Technologies

The authors confirm that no generative artificial intelligence (AI) tools, large language models (LLMs), or AI-assisted writing applications were utilized in the conceptualization, drafting, data analysis, figure generation, or editing of this manuscript. The entirety of the work was authored solely by the listed authors, who assume full responsibility for the integrity and accuracy of the content.

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