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Working with physical sciences pre-service teachers in developing computational thinking skills through concept mapping

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Abstract

This study explored using concept maps to develop computational thinking (CT) skills among Postgraduate Certificate in Education Physical Sciences pre-service teachers. Despite the increasing significance and recognition of CT skills in 21st-century education, their integration and evaluation in science teacher education is limited. This gap indicates that although CT skills are advocated in initial teacher education, teachers may lack practical development experiences. Thus, this research explored practical strategies for developing CT skills in pre-service science teacher education. Employing a mixed-methods approach, the study generated quantitative data from pre- and post-intervention questionnaires and qualitative data from reflective journals. The study involved a 6-lecture intervention within the Physical Sciences Teaching Methods course. Results showed improvement in pre-service teachers' abilities to decompose problems and identify patterns, although abstracting key concepts proved more challenging. The study contributes to the field by providing empirical evidence of the practical application of concept mapping for developing CT skills in teacher education, suggesting its potential as a valuable pedagogical tool. Further research should explore the transferability of these findings to other disciplines and in-service teachers. This study encourages further exploration into innovative pedagogical approaches for enhancing CT skills in teacher education.

Keywords: computational thinking, concept maps, pre-service teacher, science teacher education, problem-solving

Introduction

Computational thinking (CT) is a highly anticipated skill set in 21st-century education, including higher education and teacher professional development programmes including science teachers. According to Jocius et al. (2021) and Weintrop et al. (2016), 21st-century science education worldwide is embracing CT skills as an innovative pedagogical and learning strategy and supporting problem-solving competencies. Moreover, scholars and educators in science education significantly elicit evidence of teachers' and learners' higher-order thinking processes (Kamalodeen, 2022) to support the development of scientific problem-solving competencies. Thus, there is a positive correlation that science teacher education programmes can establish a basis for teachers to learn and develop pedagogical knowledge and integrate CT in teaching (Dong et al., 2023; Li, 2021). CT gained popularity after Wing's (2006) seminal paper, prompting many scholars and educators to devise various strategies to integrate and develop CT skills across disciplines, including science teacher education programmes.

The core principle of CT is systematic problem-solving competencies, and teacher education programmes should aim to achieve such competencies. As a problem-solving strategy, CT comprises the following skills as foundational skill set: decomposition, pattern recognition, abstraction, and algorithmic thinking (Dong et al., 2019; Yadav et al., 2017). Thus, Voon et al. (2023) and Angeli and Jaipal-Jamani (2018) ascertained that the rationale for promoting the development of CT skills among science pre-service teachers (PSTs) is to foster them acquire higher-order thinking skills that promote problem-solving competencies in a variety of science education contexts.

However, scholars have observed that some science PSTs have challenges in acquiring higher-order thinking skills to effectively plan for teaching science that promotes in-depth comprehension of learners' critical thinking, creative thinking, and problem-solving competencies (Marangio et al., 2024; Saavedra & Opfer, 2012). Moreover, according to Saralar-Aras and Firat (2021), most science PSTs complete their training without comprehensively acquiring appropriate competencies for organising concepts to teach, especially for short teacher education programmes such as the Postgraduate Certificate in Education (PGCE). Similarly, the South African PGCE programme, a one-year intensive teacher training course, faces challenges in adequately preparing Physical Sciences PSTs (PS-PSTs), particularly in developing 21st-century skills such as CT skills (Gravett & Petersen, 2022). Although the PGCE curriculum acknowledges the importance of 21st-century skills like CT (Ogegbo & Ramnarain, 2022; Tsakeni, 2021), the limited timeframe restricts the in-depth exploration and practical development and application of these skills, especially concerning pedagogical strategies (Dong et al., 2023).

Moreover, a compressed schedule in PGCE programmes often prioritises educational studies and traditional pedagogical knowledge coverage over modern pedagogical development (Makhechane & Mavhunga, 2021), potentially limiting PSTs' ability to develop and apply CT skills using concepts like concept mapping. Concept mapping can be adopted as a strategy for scaffolding the development of CT skills (Chen & Chung, 2024) within science education by visually representing complex scientific concepts and enabling problem-solving strategies. However, research specifically exploring the effectiveness of concept mapping for developing CT in PGCE PS-PST training remains limited (Ogegbo & Ramnarain, 2022) despite the growing emphasis on CT in 21st-century science education (Agbo et al., 2023; Yadav et al., 2017).

In light of the above background, this intervention study explores our work with PS-PSTs within the PGCE programme to develop CT skills through concept mapping. This study is led by two research questions: "How does concept mapping contribute to developing CT skills among Physical Sciences pre-service teachers?" and "What challenges do pre-service teachers encounter in using concept mapping for CT development within the PGCE Physical Sciences teaching methods course?" The objective was to investigate the impact of a concept-mapping intervention on PS-PSTs' CT skills development and explore their experiences in using this strategy. The rationale is grounded in the need to enhance pedagogical practices within the PGCE, equipping PS-PSTs with practical strategies like concept mapping to enhance CT skills in their future learners, aligning with the demands of 21st-century science education in South Africa.

Literature review

CT is considered a foundational skill set for in-service teachers and PSTs in the 21st century to support systematic problem-solving competencies in teaching. According to Wing (2006), CT uses abstraction and decomposition when dealing with a complex task or designing a large complex system. Wing (2006, p. 33) defined CT as a systematic approach that "involves solving problems, designing systems, and understanding human behaviour, by drawing on the concepts fundamental to computer science." In addition, Aho (2012, p. 832) defined CT as "the thought processes involved in formulating problems so their solutions can be represented as computational steps and algorithms." Thus, CT is concerned with problem-solving competencies and is considered a foundational skill set in addition to writing, reading, and arithmetic (Wing, 2006). The CT foundational skill set that fosters systematic problem-solving includes pattern recognition, algorithmic thinking, decomposition, and abstraction (Dong et al., 2019; Yadav et al., 2017).

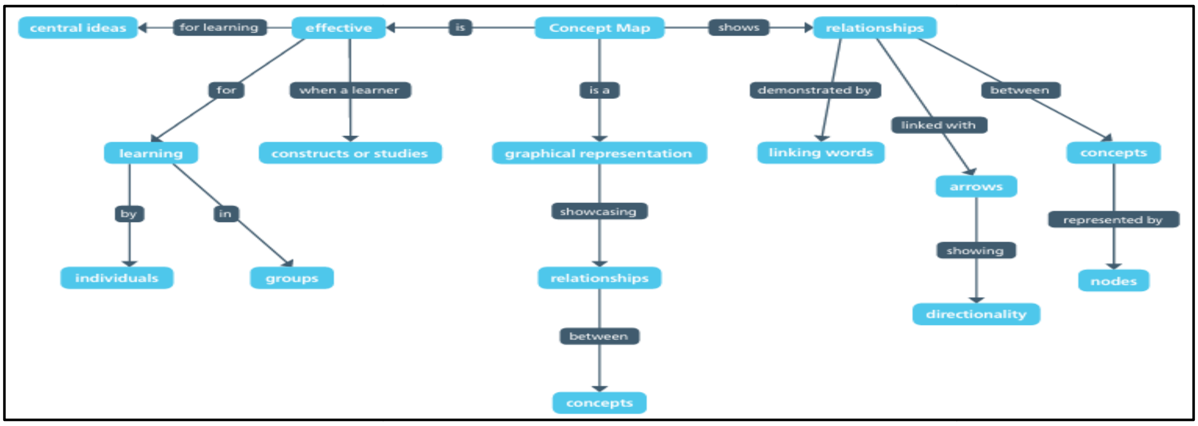
Moreover, a literature review indicates that most PSTs feel safer and more comfortable integrating CT into their future teaching if they are empirically involved in developing CT skills during their training (Dong et al., 2023; Yadav et al., 2017). According to Angeli and Jaipal-Jamani (2018), PSTs can effectively develop CT skills by engaging in various activities centred on the definition of CT. In science teacher education, CT plays various roles, such as promoting algorithmic thinking, making connections between scientific concepts, facilitating the exploration of scientific concepts through computational modelling and simulation practices, systems thinking, computational data collection, representation and analysis, and problem-solving (Kite & Park, 2022; Weintrop et al., 2016). Thus, PSTs should be well trained in CT and its application within scientific contexts to effectively integrate CT in a science discipline. Moreover, Kite and Park (2022) found that CT is seen as a way to engage learners in hands-on, inquiry-based learning and prepare them for future careers in science and technology.

Furthermore, given that the literature review reveals CT as a skill set necessary for systematic problem-solving, thus, promoting reflective thinking and purposeful goal-directed thinking among PSTs also facilitates the development of CT skills for their future learners (Li, 2021; Pasterk & Benke, 2024). Moreover, science education, such as physical sciences, requires PSTs to develop skills that facilitate logical, reflective, and realistic thinking when teaching the subject. According to Ogegbo and Ramnarain's (2022) systematic review research on CT integration into science education findings, CT fosters critical problem-solving skills and enhances PSTs' abilities to approach complex scientific inquiries algorithmically. This systematic review also revealed the importance of CT as a framework for teaching abstract science concepts. On the other hand, Tsakeni (2021), in her study, found that CT skills have the potential to assist PS-PSTs in planning for practical work even in resource-constrained environments. Thus, educators guiding PS-PSTs in these complex mental processes should choose teaching and learning strategies that move them beyond mere comprehension of teaching and learning theories to more advanced critical thinking and problem-solving competencies. However, assessing the development of CT skills among science PSTs is a challenging task. Thus, Ogegbo and Ramnarain (2022) agreed in their systematic study that it is challenging to assess CT skills in science education because there is a lack of consistent tools for developing and evaluating CT skills. They recommended devising standardised and accessible assessment methodologies that reflect teachers' and learners' CT learning processes. Thus, the concept-mapping approach is anticipated as one of the strategies to assess the development of CT skills among PS-PSTs. The use of concept mapping is deemed to enhance more practical and contextual guidance on how PS-PSTs could effectively develop CT skills through teaching methods course activities.

Concept mapping in education

Concept mapping was developed by Novak in the 1970s as a technique to promote concept visualisations by looking at the relationships between such concepts (Turan Oluk & Ekmekci, 2016). According to Novak and Cañas (2008), concept maps are constructed by selecting and writing key concepts from the text, making an attribute list of the key concepts, relating key concepts in a visual relationship, rearranging visual representations, and comparing representations to the text. Novak and Cañas further pointed out that connections or linkages between concepts should be valid and logical to represent authentic relationships between the concepts. Thus, the connections meaningfully relate the two or more concepts to consistently establish scientific understanding. These connections also enable teachers to interpret and understand the learners' conceptual thinking through their concept maps (Romero García et al., 2017). Therefore, concept maps were developed as tools to explicitly facilitate how new concepts are integrated into learners' cognitive structures. Thus, for the past 40 years, scholars and educators have used concept mapping to facilitate the meaningful learning of concepts across disciplines, including science education. Figure 1 visualises the guidelines and processes of a concept map.

Figure 1
Graphical description of a concept map adapted from Sundar (2022, p. 45)



However, constructing concept maps requires learners to actively participate in their learning process (Novak & Cañas, 2008; Romero García et al., 2017). Thus, learners such as PS-PSTs should be taught to reflect structurally on concept maps to achieve meaningful learning through theoretical and practical connections. This activity enables PSTs to arrange, link, and integrate knowledge in various ways, fostering a better understanding of solving complex problems. Although concept maps have been promoted as pedagogical tools for meaningful learning, their construction demands active engagement and reflection from learners (Novak & Cañas, 2008; Romero García et al., 2017). Such engagement requires deliberate pedagogical guidance. In particular, in science teacher education, PS-PSTs must be coached to critically analyse and structure their maps to realise learning gains beyond mere superficial mapping. Without such scaffolding, PSTs may reproduce disconnected or simplistic networks of concepts that fail to capture the complexity of scientific knowledge. This raises concerns about the necessary instructional support that should accompany concept-mapping activities, a dimension that has been underexplored. For example, a study by Angeli and Jaipal-Jamani (2018) examined PSTs' experiences with concept mapping in science education and found that many participants grappled with higher-order cognitive processes required for linking abstract ideas. These difficulties often stemmed from insufficient prior experience and a lack of explicit instruction on map construction strategies. This aligns with findings by Kulgemeyer et al. (2021), who reported that without adequate scaffolding, learners' maps tend to be fragmented and lack logical progression, impeding the intended cognitive benefits. This issue points to a gap in how concept mapping is introduced, and its differential impact depending on learners' prior experience and cognitive readiness.

Further, Novak and Cañas (2008) recommended that concept maps should embody hierarchical relationships, yet Wang et al. (2021) observed that many learners produce maps that are flat or disconnected. In their study, most learners omitted critical linking phrases or created links that were either vague or illogical, showing gaps in their conceptual understanding rather than deeper comprehension. This suggests that mastering the skill of properly articulating and visualising the connections requires instructional support beyond merely assigning mapping tasks. Similarly, Traylor et al. (2025) argued that cognitive overload might occur when learners confront complex topics without guided strategies, leading to frustration and superficial mapping. The cognitive demand to simultaneously manage multiple concepts, their interrelations, and the appropriate hierarchical structure can overwhelm learners, reducing the effectiveness of the approach.

There are different ways of constructing concept maps, for example, learners can construct them through paper-based (unplugged) or computer-based (plugged-in) approaches. Some examples of computer-based concept-mapping tools include MindMup (http://www.mindmup.com/), Edrawmind (https://www.edrawsoft.com/ad/edrawmind/), and Mindomo (https://www.mindomo.com/). These multifunctional applications also facilitate incorporating digital information into the map, collaboration, and easy updating. Both paper-based and computer-based concept-mapping approaches promote meaningful learning by allowing learners and teachers to connect key concepts by cross-linking them and adding relevant examples to support their argument (Chen & Chung, 2024). Thus, identifying and using cross-links in concept-mapping activities is vital in developing CT skills such as decomposition, abstraction, pattern recognition, and algorithmic thinking. Yet, it is important to recognise that digital technologies do not automatically guarantee effective learning outcomes. Learners may focus more on the mechanics of software use than on the conceptual structuring itself. Moreover, excessive reliance on technology can distract from the cognitive processes essential to decomposing, abstracting, and recognising patterns—critical CT skills (Dong et al., 2019). This dilemma shows a challenge in providing learners with sufficient technical mastery without compromising the core cognitive objectives.

Previous studies have noted the need to incorporate concept mapping in science education and for developing CT skills. According to Garner et al. (2020), using concept maps in the classroom improves learners' understanding of scientific concepts such as chemistry concepts, particularly when used in small-group settings. He also observed that learners who created concept maps had a deeper comprehension of complex topics in chemistry like atomic structure, chemical bonding, and moles. Additionally, Machado and Carvalho's (2020) study revealed that concept maps are effective in helping learners organise and represent their knowledge visually, which positively impacts their cognitive processes and academic performance. For example, suppose learners organise knowledge in a hierarchical or non-hierarchical structure. In that case, they can better relate new information to prior knowledge, facilitating long-term memory and deeper comprehension and conceptualising CT skills such as abstraction, algorithmic thinking, and pattern recognition. Machado and Carvalho further pointed out that using concept maps enhances learners' problem-solving skills, creativity, and ability to identify relationships between concepts. Xu et al. (2024) also observed that concept maps enable self-learning as learners actively organise and consolidate knowledge. Thus, concept maps support learners in organising concepts clearly and logically and help teachers convey relationships between topics effectively. Furthermore, Cañas and Novak (2014) ascertained that allowing learners to revise and refine their concept maps increased the average number of concepts and connections in the maps. However, divergent perspectives exist; Chen and Chung (2024) found that some PSTs perceive concept-mapping activities as additional burdens rather than valuable learning strategies. This perception parallels scepticism noted by Dong et al. (2023), who suggested that the benefits of constructivist strategies like concept mapping are not universally accepted or experienced across PSTs. If learners fail to see the relevance or utility of mapping, their motivation to invest cognitive effort diminishes, which may explain why some maps remain simplistic or disconnected despite repeated practice.

The literature also reveals the relationship between CT and concept maps. For example, Xu et al.'s (2019) research on the application of concept maps in the study of CT training found that concept maps are effective tools for improving learners' understanding of CT principles because they help them to visualise and organise complex CT concepts, making it easier to grasp abstract ideas and their relationships. Thus, using concept maps in CT training can lead to better breaking down of problems into structured visual maps, and learners can analyse problems better and develop solutions systematically. In addition, concept maps promote collaborative learning as learners work together to create and discuss the maps and experience higher levels of engagement (Machado & Carvalho, 2020). Xu et al. (2019) further pointed out that the visual nature of concept maps supports better retention of CT concepts because learners can more easily recall and revisit interconnected ideas. Thus, concept mapping provides an interactive and dynamic way to learn CT, benefiting both visual and analytical learners.

Furthermore, Xu et al. (2019) found that both teachers and learners found concept maps useful in the teaching and learning processes by helping to clarify complex concepts and foster deeper understanding. However, the CT and concept-mapping fields remain underexplored, particularly in the initial physical sciences teacher education programmes. Thus, this current research investigates how PGCE PS-PSTs, through concept-mapping activities, would make the development of CT skills visible.

Theoretical framework

This study draws upon Kolb's (1984, p. 41) experiential learning theory (ELT) as its guiding framework, according to which, learning is "the process whereby knowledge is created through the transformation of experience. Knowledge results from the combination of grasping and transforming experience." According to Kolb, ELT advocates that learning is a cyclical process involving four distinct phases: concrete experience, reflective observation, abstract conceptualisation, and active experimentation. Therefore, learning begins with a concrete experience to provide a foundation for subsequent reflection. Through reflective observation, PSTs analyse and interpret their experiences, making connections and identifying patterns (Cunliffe & Easterby-Smith, 2017). This process leads to abstract conceptualisation, where PSTs formulate general principles and theories based on their reflections (Kulgemeyer et al., 2021). This cyclical progression, moving from concrete experience to active experimentation, allows PSTs to transform experience into knowledge construction. Moreover, Kolb asserted that effective learning requires movement through all four phases. In this study, PS-PSTs engaged in concept-mapping activities that served as concrete experiences. They then reflected on these experiences, observing patterns and relationships between concepts. This reflective observation led to abstract conceptualisation, which aligns with CT principles. Also, they actively experimented by applying their understanding to new concept-mapping exercises, solidifying their learning, and developing practical skills. This study assumed that by engaging in these four phases, PS-PSTs would develop CT skills and apply them in science education. The PSTs were involved in constructing concept maps individually and collaboratively in the context of the teaching methods course activities.

Methodology

Research design

This study employed a mixed-methods research design that combined both quantitative and qualitative approaches to data generation (Creswell & Creswell, 2018) to assess the development of CT skills among PS-PSTs through concept mapping. Qualitative data were generated through reflective journals and participants' artefacts (concept maps), while quantitative data were generated through pre- and post-tests (concept maps questions only). The study was an intervention case study and was conducted for six lectures in a 6-week term period with PGCE PSTs in the Physical Sciences Teaching Methods course. Each lecture was allocated two hours as per the structure of the PGCE programme. Focusing on a group of PS-PSTs as participants allowed for an in-depth exploration of their voices and experiences as sources of data through reflective journals (Mertens, 2023). All PSTs registered in the PGCE Physical Sciences teaching methods course participated in this study. We introduced the concept of concept mapping to participants using paper-based and computer-based approaches after they had completed answering the pre-test questionnaire.

Participants and context

A total of seven PS-PSTs who enrolled in the PGCE programme at the Faculty of Education at one of the universities in Eastern Cape participated in this study. Participants were purposively sampled (Merriam, 2015) to include all seven PSTs registered for the Physical Sciences Teaching Methods course. The participants consist of three men and four women, ages ranging from 24 to 29 years, and pseudonym codes (PST 1 to PST 7) were allocated. In this intervention, concept-mapping activities were based on paper-based and computer-based approaches. Thus, the first author used his knowledge as a physical sciences teacher educator to lead the flow of concept-mapping activities in the course.

However, none of the participants in this study had used computer-based concept-mapping software before. Hence, PSTs were introduced to computer-based concept-mapping software. In this study, a free online concept-mapping software, Mindomo, was used. This software allows users to create, download, save, and retrieve concept maps in various formats compatible with Microsoft applications. Also, it enables users to edit, share, and export concept maps in different formats such as jpeg images. This facilitated the creation and manipulation of concept maps during the study. The subsequent activities involved constructing concept maps based on provided keywords and phrases, both on paper and using the Mindomo web-based software. Participants also constructed concept maps to summarise their plan to teach a particular topic.

Activities in the CT intervention

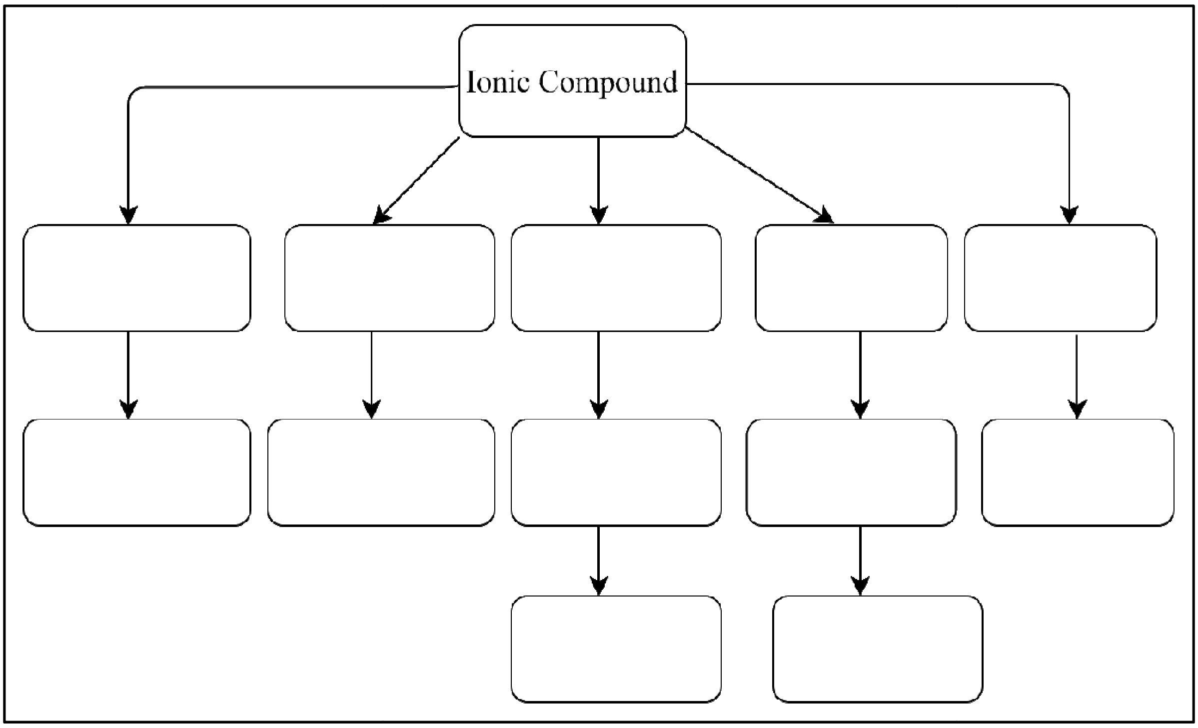
The intervention consisted of four carefully structured sessions designed to progressively support the development of CT skills among PS-PSTs through concept-mapping tasks.

Session 1

The initial session served as a baseline assessment of the PSTs' current capabilities. The second author provided a paper-based concept-map template with a clear central topic (see Figure 2). Participants received an unordered list of keywords and phrases, which they had to arrange correctly within the concept-map framework. This task targeted foundational CT skills, particularly decomposition and pattern recognition because the PSTs needed to identify relevant concepts and organise them logically. Two parallel tasks, one chemistry-focused and one physics-focused, were completed as part of both pre-test and post-test assessments. The maps produced allowed researchers to gauge the participants' entry-level proficiency before any explicit intervention on CT was introduced. This preparation laid the groundwork for the subsequent development of abstraction and algorithmic thinking skills.

Figure 2

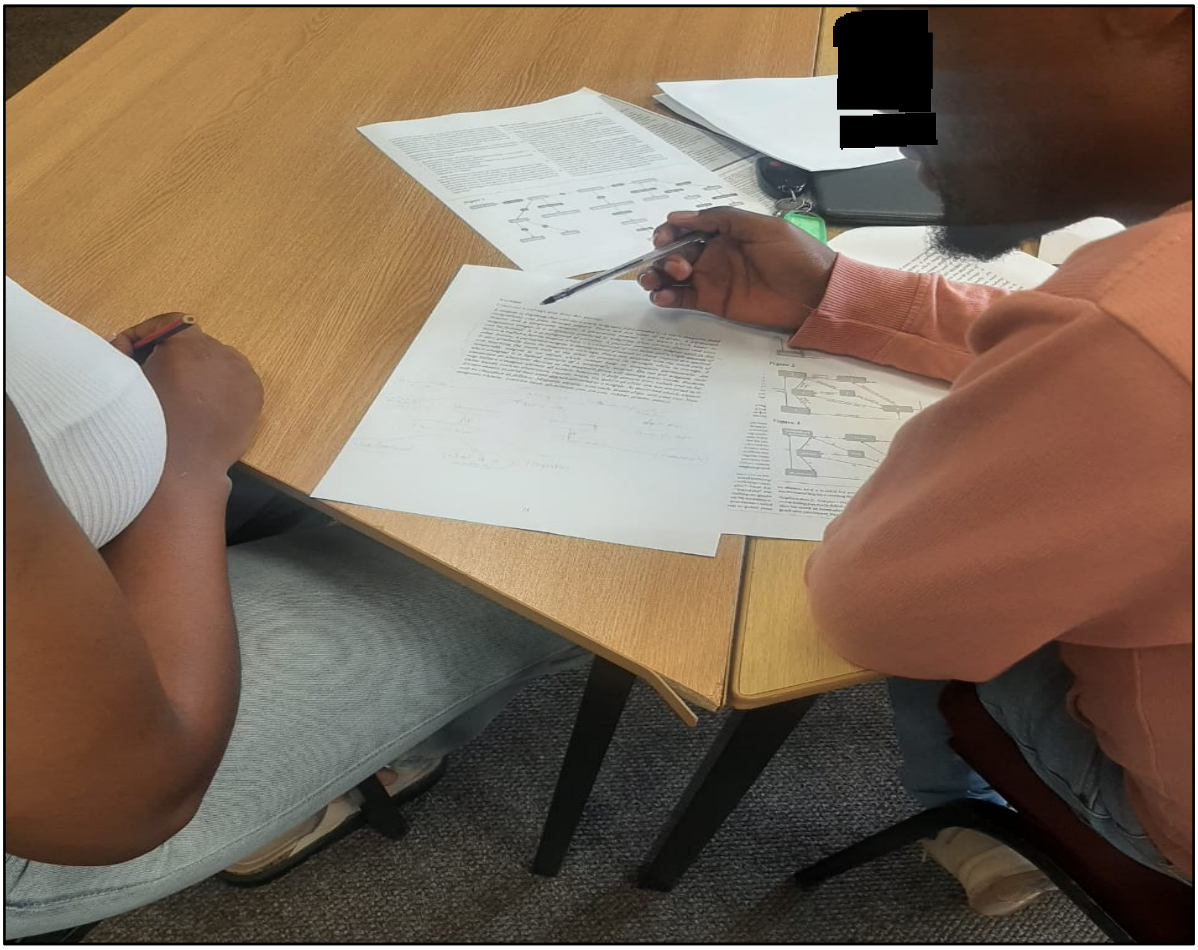
A sample of a concept map engaged in the study with PSTs



Session 2

In the second session, concept-mapping activities became integrated within the course lectures. The PSTs received a passage about magnetism and were asked to construct a concept map reflecting the key ideas and their relationships. The first author provided concrete examples by explaining the creation of a sample concept map (see Figure 1), which illustrated the stepwise process of connecting concepts. This session emphasised the transition from concrete experience to reflective observation within Kolb's (1984) experiential learning cycle. The PSTs engaged in active analysis of the content and developed skills in decomposing complex information and identifying relevant patterns (see Figure 3). Understanding the time constraints in the PGCE methods course, participants were permitted to complete concept-map tasks outside lecture hours, supporting their individual learning paces. Moreover, the inclusion of both chemistry and physics topics was intentionally adopted with an understanding of the mixed academic backgrounds of the PSTs, ensuring relevance and encouraging cross-disciplinary skills transfer (PSTs enrolled in the course have a background in chemistry, physics, or both).

Figure 3
PSTs collaboratively analysing the passage to identify key concepts



Session 3

This session continued building on earlier skills with a focus on abstraction and algorithmic thinking. The PSTs created concept maps for four significant topics from the Physical Sciences CAPS document for Grades 10–12: chemical bonding, chemical change, mechanics, and electricity and magnetism (Department of Basic Education, 2011). They employed both paper-based and computer-based tools to construct these maps. The use of multiple modalities aimed to enhance flexibility and technical proficiency while reinforcing the extraction and visual representation of key information from dense scientific texts. The first author provided guidance to help PSTs abstract core concepts and sequentially organise them, key components of CT. This activity offered them the ability to break down complex topics into understandable parts and to structure those parts systematically, thus strengthening their algorithmic thinking.

Session 4

The final session functioned as a summative review through a post-test identical to the initial pre-test, allowing for a direct comparison of changes in CT skills proficiency. In addition to the post-test, participants wrote reflective journals describing their experiences during the intervention. This reflective task encouraged deeper metacognition, helping PSTs to articulate how concept mapping influenced their CT development. Through this reflection, they engaged with the phase of active experimentation in Kolb's (1984) learning cycle. Writing reflections not only reinforced their understanding but also facilitated the transfer of these skills into future teaching practice, promoting the integration of CT strategies into their pedagogical repertoire.

Data analysis

Data analysis in this study used a mixed-methods approach (Creswell & Creswell, 2018), combining quantitative and qualitative data to assess the development of CT skills. Quantitatively, a CT rubric from Pollock et al. (2019) was used to measure the PSTs' proficiency (with Level 1 being the lowest and Level 4 being the highest proficiency) in decomposition, abstraction, algorithmic thinking, and pattern recognition before and after the intervention, allowing for clear, systematic comparison of skill improvements. Qualitative data were gathered from participants' reflective journals, which were thematically analysed using inductive thematic analysis following Merriam (2015) and Clarke and Braun (2017) to identify common themes regarding participants' experiences, challenges, and perceptions related to concept mapping. The integration of these data sources provided a comprehensive understanding of both objective skills development and subjective learning processes. The reflective journals were coded to extract meaningful categories, allowing identification of patterns such as initial uncertainty about concept mapping's purpose and the need for explicit instruction and ongoing support. The mixed-methods approach facilitated triangulation, enhancing validity by corroborating quantitative improvements with qualitative insights into the PSTs' metacognitive and experiential learning. Quantitative scores were presented graphically to illustrate changes across individual PSTs and CT skill areas, helping to visualise the intervention's impact.

Findings of the study

This section presents the key findings regarding the use of concept-mapping activities for developing CT skills among PS-PSTs in the PGCE programme. The results reveal significant advancements in the PSTs' abilities to decompose complex problems, recognise patterns, abstract key concepts, and apply algorithmic thinking strategies as a result of the intervention.

Concept-map activities and PSTs' development of CT skills

In this study, PS-PSTs were tasked to design concept maps for four topics of the Physical Sciences CAPS that demanded the application of their analytical thinking, critical thinking, and problem-solving skills. The major activity in the intervention was concept mapping using both plugged-in (computer-based) and unplugged (paper-based) approaches. Figures 4A and 4B show concept maps constructed by PST 1 and PST 4, respectively using unplugged approaches. Participants were tasked to work on a chemical bonding (for example, ionic compound) problem to construct a concept map. They were given the following keywords which are not orderly arranged: $CaCl_2$, conduct electricity, positive ions, solids, an aqueous state, molten state, negative ions, anions, non-volatile, Ca^{2+}, Cl^-, cations, strong forces of attraction. Figure 4A shows PST 1's, and Figure 4B shows PST 4's first attempts at the task.

Figure 4
Organising key concepts of ionic compounds into a concept map

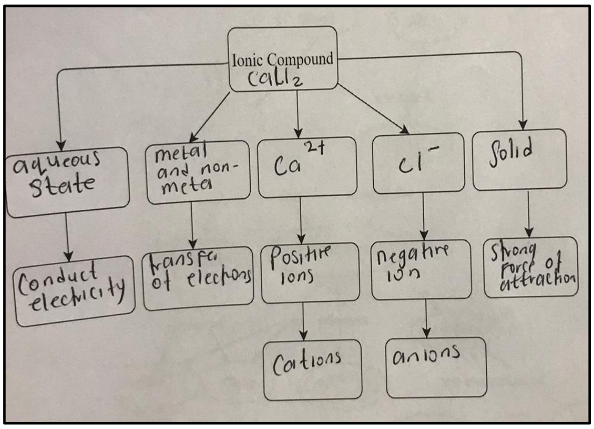


Fig. 4A

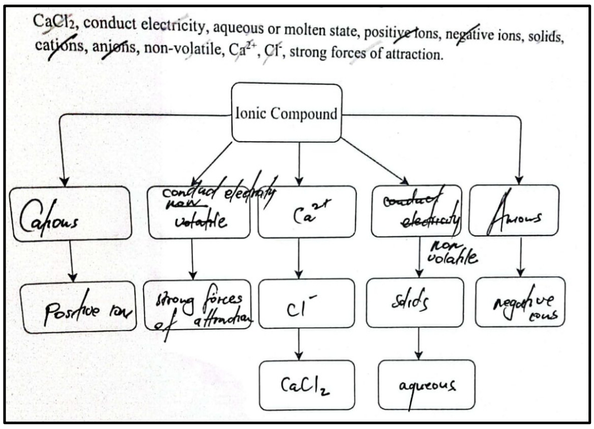
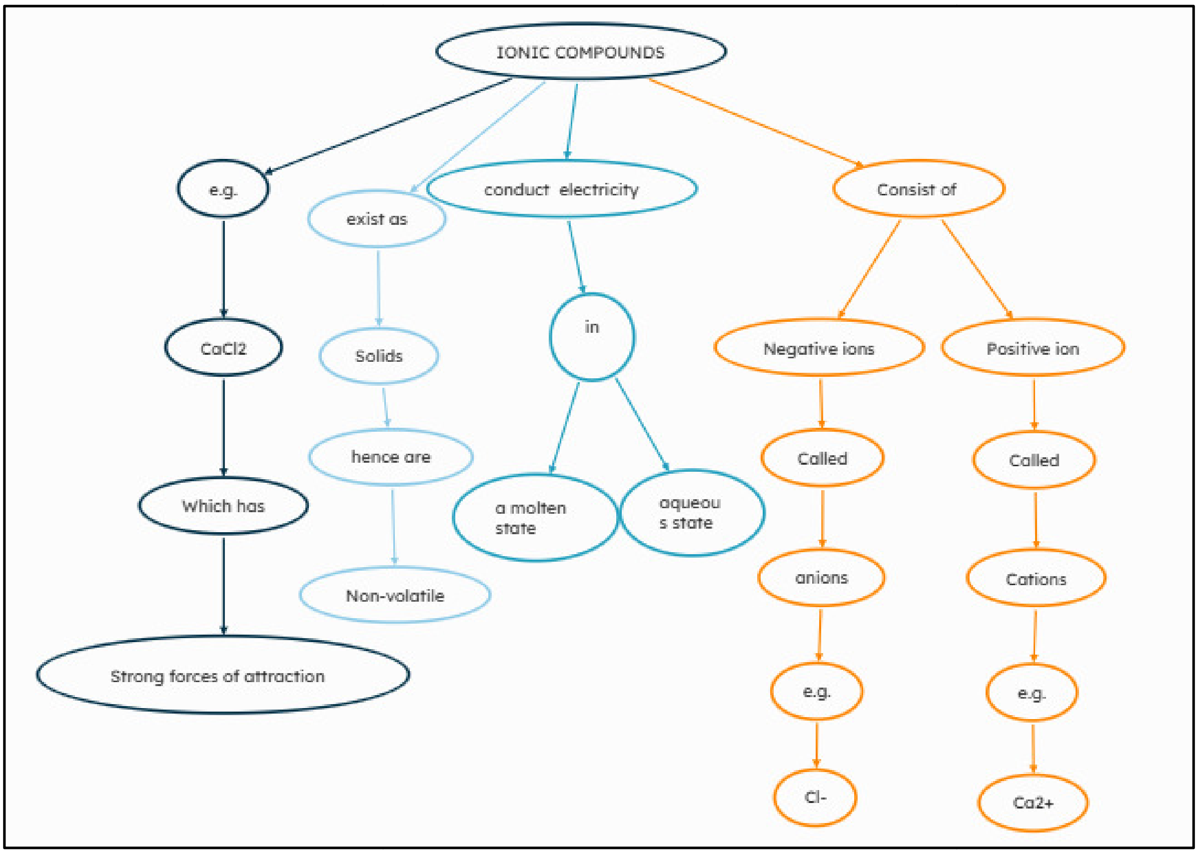


Fig. 4B

After participants were introduced to constructing concept maps using the unplugged approach, they were also instructed to reconstruct the concept maps they constructed using the plugged-in approach. Figure 5 depicts the final concept map PST 6 constructed using Mindomo software. In this task, participants were instructed to provide cross-links or connecting words in order to make the concepts scientifically meaningful. Participants were free to choose connecting words from this list: e.g., in, which has, are called, hence are, consist of, exist as.

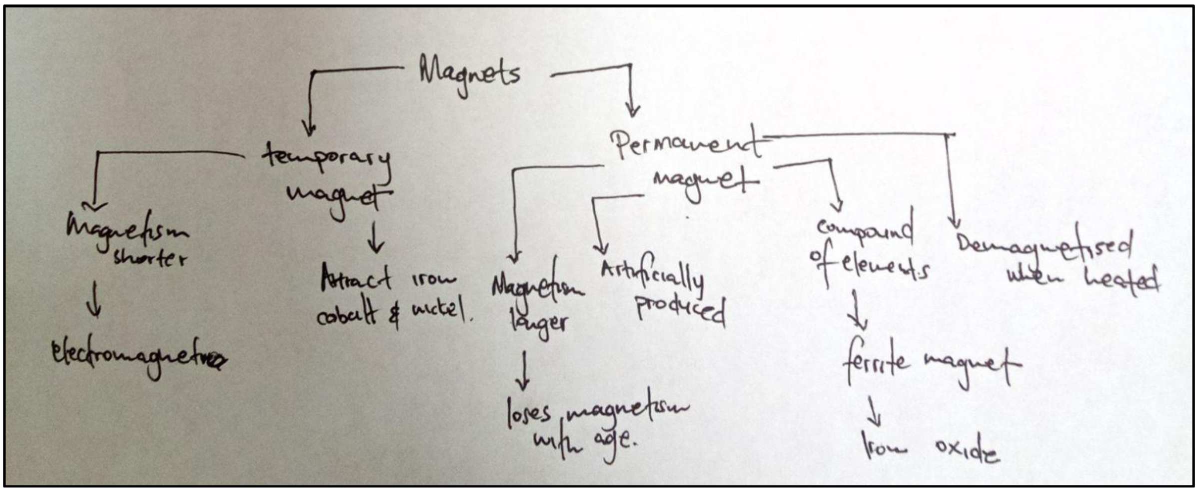
Figures 4 and 5 reveal the progress of participants' understanding of concept mapping to decompose complex problems and apply abstraction competencies to solve contextual problems. It is clear that the results in Figure 4 reveal that PST 1 and PST 4 struggled to demonstrate decomposition and abstraction skills in order to visually organise the concepts. However, after being involved in the intervention activities, PSTs improved their concept-mapping competencies and were able to break down problems and filter out irrelevant information to construct a meaningful concept map, as presented by PST 6's concept map in Figure 5.

Figure 5
Ionic compound concept map constructed using Mindomo software (plugged-in approach)



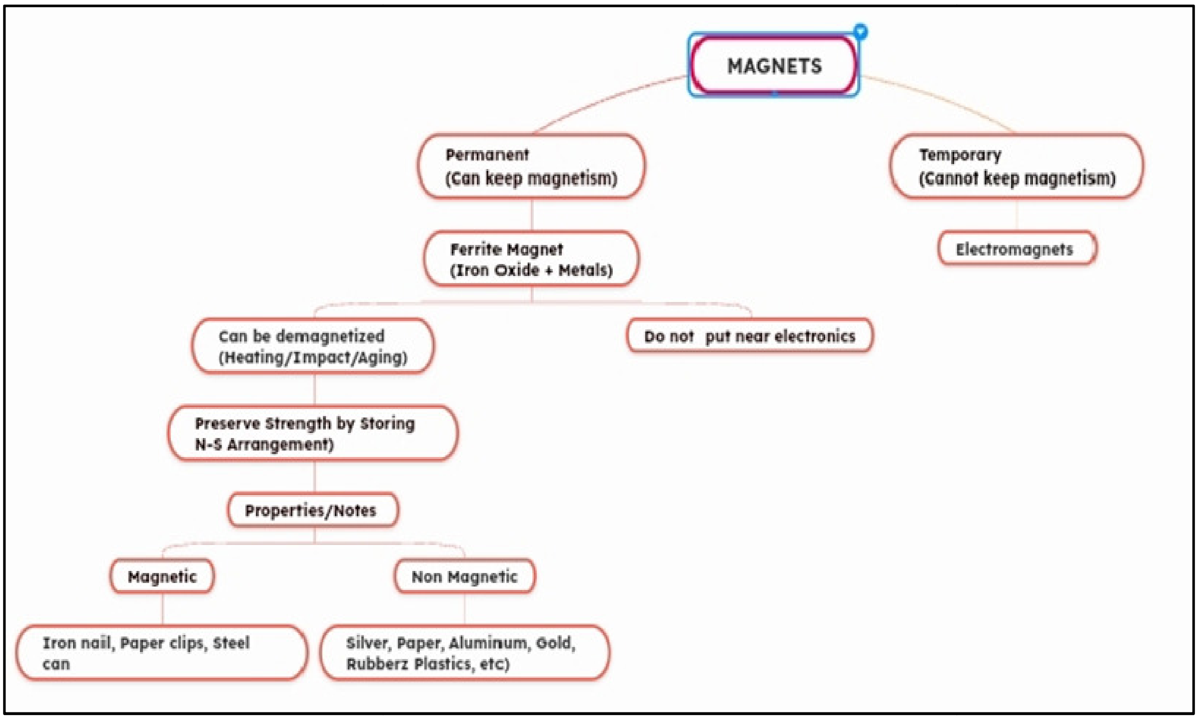
Moreover, participants worked on a physics-related task (see Appendix A) to construct a concept map. Figures 6 and 7 show work extracted from PST 2 and PST 7, respectively.

Figure 6
Magnetism concept map constructed through a paper-based (unplugged) approach



Figures 6 and 7, drawn from PST 2 and PST 7, respectively, show concept maps constructed using both unplugged (Figure 6) and the plugged-in (Figure 7) approaches. Figure 7 shows a concept map PST 7 constructed using Mindomo software, which is a web-based concept-map tool to automate the generation and connect the key concepts from the magnetism passage topic.

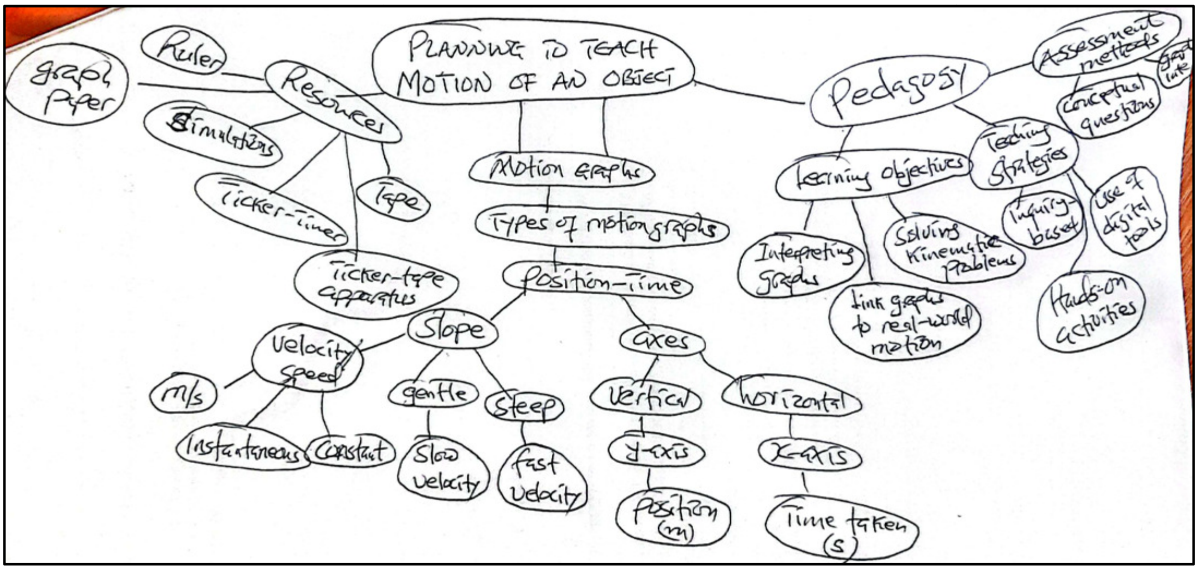
Figure 7
Magnetism concept map constructed through plugged-in approach



Similarly, Figure 8 shows a concept map constructed by PST 5. PST 5 developed the concept map showing how she planned to teach the concept "Description of Motion," which is under the topic of Mechanics, by analysing the Physical Sciences CAPS document content on page 56 and content as provided in Study and Master Physical Sciences CAPS Learner's Book Grade 10 from pages 278 to 286 (Department of Basic Education, 2011). This concept map summarises key concepts, resources required, and how to teach the topic (pedagogy).

PST 5, like others in the study, developed the concept map in Figure 8 after receiving instruction on various concept-mapping techniques and methods. The task required the participants to extract key concepts from one of the four selected topics and integrate them into a coherent, unplugged concept map. This process enabled the development of abstraction skills, a crucial component of CT, by requiring participants to identify core ideas and represent them in a generalised form within the concept-map framework.

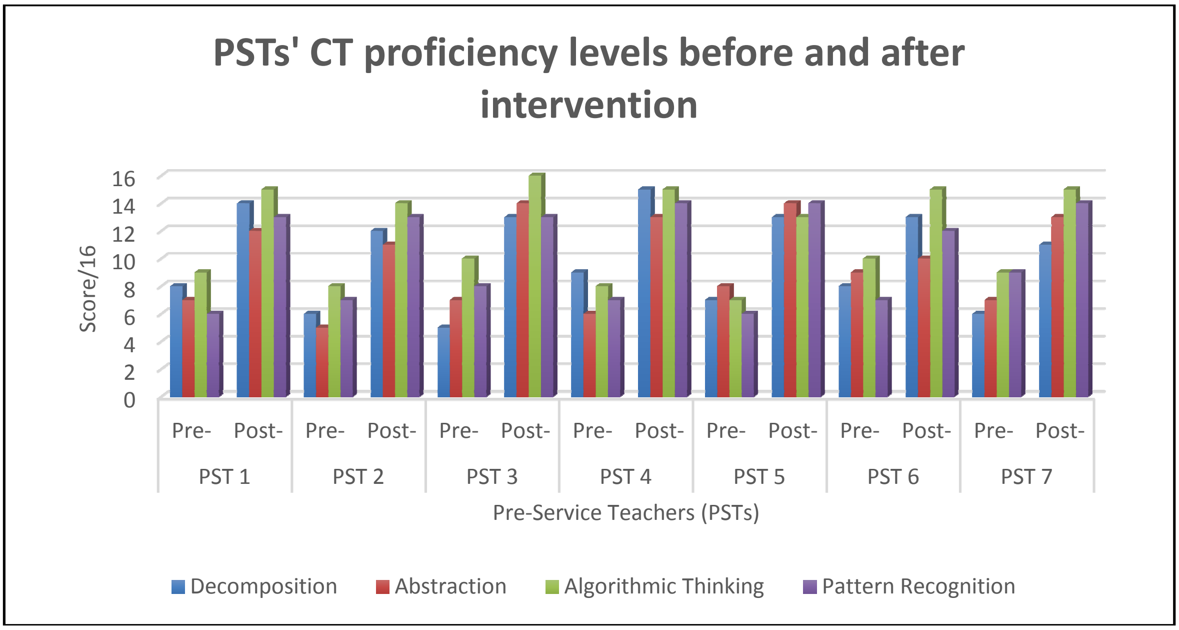
Figure 8
Unplugged concept map summarising how to teach the motion of an object



PSTs' proficiency levels of CT skills before and after intervention

This section details the effectiveness of the intervention by examining the proficiency levels of CT skills among participants before and after the intervention using a CT rubric, and analysed in Microsoft Excel. As illustrated in Figure 9, the data reveal a significant shift in proficiency levels. Figure 9 also shows that the majority of PSTs demonstrated limited foundational CT skills prior to the intervention.

Figure 9
The proficiency level of foundational CT skills before and after intervention



The findings in Figure 9 indicate significant improvements in the proficiency levels of algorithmic thinking, decomposition, and pattern recognition among the PSTs following the intervention. Participants demonstrated enhanced algorithmic thinking skills, which can be attributed to their experiences constructing detailed concept maps during the intervention. These activities required them to analyse assigned topics and scientific concepts in sequential steps, reinforcing their ability to develop algorithms for problem solving. Decomposition skills were similarly enhanced as most PSTs excelled in separating scientific ideas into manageable components. This improvement is directly linked to the hands-on concept-mapping exercises they undertook, which focused on identifying key concepts from the four physical sciences subject topics and representing them visually. As participants engaged in these activities, they practised dissecting larger problems, strengthening their decomposition skills.

The increase in pattern recognition is also reflected in Figure 9. This relates to the fact that participants were able to identify relationships and connections among various scientific concepts as they organised their concept maps. This was particularly evident in concept maps on the chemical changes topic, and the electricity and magnetism concept, where they visually connected similar themes. However, the improvements in abstraction were less compared to the other areas. This can be attributed to the inherent challenges participants faced in filtering out less relevant details when summarising complex content in the Physical Sciences CAPS document (Department of Basic Education, 2011).

Challenges participants encountered when constructing concept maps

Several challenges emerged regarding the development of concept mapping for CT among PSTs in the study. Many participants struggled with the initial process of constructing concept maps. The reflections in their journals expressed difficulties in organising concepts logically, with PST 1 and PST 6 stating:

> I found it tough to connect each idea in a way that makes sense. (PST 1)
>
> Sometimes it feels like there is just too much to think about, making it hard to see how everything fits together. (PST 6)

This shows that a lack of understanding about effectively creating concept maps limited the PSTs' ability to use this concept mapping to enhance CT skills. Concept mapping required the participants in this study to identify key concepts, organise them hierarchically and establish meaningful connections between them.

Some participants expressed frustration regarding integrating concept mapping into the overall curriculum. Participants PST 3 and PST 7 noted:

> I often struggle to see how concept mapping actually helps with teaching science . . . it feels more like an extra task than a useful tool. (PST 3)

> Sometimes I feel that my time could be better spent on other tasks because I do not fully see the value of concept maps. (PST 7)

This indicates a lack of clear connection between the curriculum and the practical use of concept mapping. PSTs needed to understand how concept mapping could be applied to teaching physical sciences and how it contributes to their professional development. Similarly, some participants found it challenging to transition from concrete content to abstract concepts. As noted by PST 4:

> Breaking down complex scientific ideas into simpler parts is harder than I thought; I don't have enough experience.

Thus, this points to significant obstacles the participants encountered in engaging with CT through concept mapping given that abstraction is a key skill that requires practice. CT in this study involved drawing abstract concepts from the assigned topics and articles. The PS-PSTs needed ongoing support in developing the ability to represent these abstract concepts effectively in their concept maps.

Discussion of findings

This interventionists study's findings demonstrate the important role concept mapping plays in enhancing PSTs' CT skills. The integration of concept mapping into the methods course for PGCE PS-PSTs demonstrated notable improvements in their ability to understand complex scientific concepts. This concurs with research by Xu et al. (2019), which illustrated how concept maps facilitate the visualisation and organisation of CT principles, allowing learners to break down problems more effectively and grasp abstract relationships. However, it is important to note that in the South African PGCE context, most PSTs face unique challenges stemming from systemic educational inequalities and limited exposure to advanced pedagogical strategies. Thus, Khoza and Maseko (2024) and Mosabala (2025) argued that most PSTs in such contexts experience difficulties bridging theoretical knowledge and classroom practice, which can influence how concept-mapping interventions are received and enacted. The improvements observed in our study, therefore, reflect not only the efficacy of the intervention but also the adaptability of concept mapping to address specific contextual learning barriers faced by South African PSTs.

Further, the study revealed significant improvements in the proficiency levels of algorithmic thinking, decomposition, and pattern recognition among the PSTs (see Figure 9) following the intervention, while the development of abstraction skills was less noted. This aligns with the research by Dong et al. (2019) and Yadav et al. (2017), which observed the foundational role of these specific CT skills in enhancing problem-solving abilities in initial teacher education contexts. Similar findings have been reported by van Wyk and Waghid (2023), who demonstrated that while PSTs at a selected South African teacher education programme quickly grasp procedural skills such as algorithmic thinking, developing higher-order cognitive skills like abstraction remains a significant challenge due to limited prior experience with abstract scientific reasoning. The PSTs' ability to create detailed concept maps demonstrates their growth in algorithmic thinking, revealing their CT skills in breaking down tasks into sequential steps. This progression is linked to Kolb's (1984) ELT adopted in this study, which posits that knowledge is constructed through transforming experience, offering the role of active experimentation and reflective observation. Nevertheless, in South African PSTs, the translation of concrete knowledge to abstract reasoning may require additional scaffolding because educational disparities often result in uneven familiarity with abstract scientific terms and conceptual frameworks (Ogegbo & Ramnarain, 2022), influencing PSTs' readiness for abstraction.

Similarly, participants such as PST 1 and PST 4 demonstrated significant struggles in organising their concept maps, manifesting the challenges in abstract conceptualisation as outlined in Kolb's (1984) theory. Although they engaged with concrete tasks, PST 4's reflections on breaking down complex ideas reveal that transitioning from concrete experience to abstract thinking requires further support and practice. This struggle supports findings from Angeli and Jaipal-Jamani (2018), which indicate that PSTs tend to grapple with higher-order thinking skills due to lack of experience or confidence. However, this contrasts with the hypothetical findings of Krajcik and Shin (2023), who suggested that even novice learners can readily adapt to concept mapping with minimal guidance. Such discrepancies may be attributed to variations in the specific training provided to participants or differences in the complexity of the targeted concepts. Moreover, Ajani and Govender (2024) found that most PSTs enter teacher education programmes in South Africa with heterogeneous academic backgrounds, which affects how quickly they adapt to pedagogical innovations.

Reflective journals revealed that some participants felt overwhelmed by the initial task of constructing concept maps, particularly when dealing with complex scientific concepts. Concurring with Kulgemeyer et al.'s (2021) findings, this suggests the importance of providing explicit instruction and ongoing support during the initial stages of concept-mapping implementation. The study observed limited improvement in abstraction skills among PS-PSTs, which also concurs with Machado and Carvalho's (2020) findings that while concept mapping can enhance deeper cognitive processing, effective integration is crucial. Reflective journals from PST 3 and PST 7 indicated initial uncertainty about the purpose and value of concept mapping in teaching physical sciences. However, over time, their developing concept maps demonstrated a deeper understanding of how concept-mapping aids in organising and synthesising complex information. This progression also led them, along with other participants, to appreciate the tool's potential not only for their own learning but also as a pedagogical asset in teaching science concepts. This shift reveals the intervention's dual impact on enhancing CT skills and shaping PSTs' beliefs about effective science teaching practices.

Nonetheless, differences in individual prior knowledge and familiarity with concept mapping influenced the intervention's effectiveness. For example, PST 3's scepticism about the usefulness of concept mapping in their future teaching mirrors concerns raised in other studies (Chen & Chung, 2024; Machado & Carvalho, 2020), where some PSTs perceived such pedagogical tasks as burdens rather than beneficial strategies. This resonates with broader literature presenting limitations in CT interventions within teacher education, indicating that constructivist strategies like concept mapping do not uniformly benefit all PSTs (Dong et al., 2023). Therefore, we argue for structured and context-sensitive scaffolding strategies, which are critical to enhancing PSTs' confidence and competence in managing abstract scientific content through visual representations such as concept maps.

Conclusion

This study investigated the effectiveness of concept mapping in developing CT skills among PGCE PS-PSTs. The findings reveal that integrating concept mapping into the teaching methods course significantly improved PSTs' abilities to decompose complex problems, recognise patterns, and understand key concepts. These improvements align with existing research revealing the role of concept maps in visualising and organising complex information. This research contributes to the field by demonstrating the practical application of concept mapping in a teacher education context, specifically within a Physical Sciences Methods course. It addresses a gap in existing literature by providing empirical evidence of the practical use of concept mapping on PSTs' CT skills development. The limitation of this study is the substantial individual variability in participants' prior knowledge and familiarity with concept mapping, which affected their ability to effectively engage with the intervention and develop CT skills. Additionally, participants experienced cognitive overload when working with complex physical sciences content, hindering their ability to construct meaningful concept maps and limiting the scalability of this approach. Future studies should investigate tailored scaffolding strategies that accommodate individual differences to enhance concept-mapping efficacy. Moreover, exploring the transferability of these findings to other disciplines and in-service teachers is recommended.

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Appendix

A magnet is anything that carries a static magnetic field around it. A static magnetic field (magnetism) can pass through papers. There are two types of magnets, a permanent magnet and a temporary magnet. A permanent magnet is an object which keeps its magnetism longer. It is artificially produced in industries (thus various shapes and sizes can be formed). It is a compound of elements. A popular permanent magnet used in this lesson is called a ferrite magnet which is a compound of iron oxide and a slight amount of other metals. A permanent magnet is demagnetised if heated or sharp impacts are applied. It also gradually loses its magnetism with age. Place two magnets with the north pole of one touching the south pole of the other to preserve its strength while in storage. A temporally magnet is an object which cannot keep its magnetism permanently. An electromagnet is a typical example of a temporally magnet. Do not put magnets near computers or electronic devices as the magnetic force will damage parts inside. Students may believe a magnet attracts all metals; however, it only attracts iron, cobalt and nickel. Other metals such as aluminium, copper, brass, tin, gold and silver are not attracted to it. All non-metals in solid their state are not attracted to a magnet. As described above, objects will be classified as follows; Magnetic objects: iron nails, paper clips, and steel can. Non-magnetic objects: exercise book, aluminium can, tin can, rubber, plastic, pencil.