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How do pre-service teachers integrate knowledge when reflecting on a pedagogical situation? An analysis of concept maps in teacher education

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The use of professional knowledge (from different areas; content knowledge, pedagogical knowledge, pedagogical-psychological knowledge)—that is, scientific evidence in the broader sense—can help teachers to act professionally in complex pedagogical situations. An important part of the professional use of evidence is the integration of various components of knowledge. Existing research evaluates knowledge integration dichotomously or refers to multiple document research, although we assume that the structures are more complex and should be taken into account when promoting knowledge integration of prospective teachers. Concept maps—that represent mental structures—enable a detailed assessment of structures of integrated knowledge. The aim of this study is to work out differentiated structures of knowledge integration. In a field setting, 33 master's students (primary science education) designed concept maps to analyze a given pedagogical situation. The maps were coded structurally and thematically. Additionally, graph theoretical measures were applied. Results show three types of knowledge integration that we call *Interrelation*, *Side-by-Side Integration* and *Merging*. We discuss these types in terms of theoretical implications and possible benefits for teacher education. A differentiated analysis of structures of knowledge integration can be used to create individualized learning opportunities.

KEYWORDS

teacher professional knowledge, knowledge integration, concept maps, mental models, evidence-based teaching, teacher education, pre-service teachers

1 Introduction

Imagine a primary science education teacher is preparing a lesson on digestion. To do so, the teacher needs content knowledge (CK) (Shulman, 1986) about organs and the process of digestion. Planning also requires pedagogical content knowledge (PCK) (Shulman, 1986) to present the information in a learner oriented yet technically correct way and to choose an appropriate method with its correct implementation. To create an activating learning environment, the teacher needs to know about principles of classroom management and motivation (pedagogical psychological knowledge; PPK, Voss et al., 2011). When implementing the lesson, the teacher needs (among other things) knowledge about existing misconceptions of the students (PCK), subject-specific fact knowledge to answer pupils' questions (CK) and a variety of pedagogical concepts, e.g., attribution theory (PPK). When only paying attention to one piece of information at a time, crucial other aspects may be neglected.

This example illustrates the fact that, in their daily pedagogical practice, teachers act in complex situations which are characterized by uncertainty as well as conflicting or complementary objectives (Cramer et al., 2023; Tatto, 2021). One way to deal with this uncertainty is referring to evidence-based knowledge. According to a moderate understanding of evidence (Stark, 2017; Wilkes and Stark, 2023), this also includes the entire professional knowledge that prospective teachers acquire during their studies, for instance. As the example at the beginning illustrated, it is important to integrate knowledge components from different sources. Richter and Maier (2017) argue that an incorrect handling of information can lead to an incorrect assessment of scientific evidence, a one-sided understanding, and misconceptions when dealing with controversial topics. These findings are applicable to teachers' knowledge: If knowledge from different sources is not conscientiously related and evaluated, a mental model shaped by distorted beliefs (e.g., about the effectiveness of homework) can develop and be put into action. Existing research on the structure of mental models with integrated knowledge mainly assesses (though not conceptualizes) knowledge integration with dichotomous instruments (e.g., Zeeb et al., 2020) or with close reference to multiple document research (e.g., Hartmann et al., 2021). However, we assume that a dichotomous assessment of knowledge integration may not be appropriate as, for example, there may be differences between explicitly and implicitly integrated knowledge. Moreover, the development of expertise and, as part of this, the acquisition and integration of knowledge are not a dichotomy, but a process (Berliner, 2004). The conceptualization and assessment of knowledge integration with reference to multiple document learning is more differentiated, but in pedagogical practice, teachers often have to recall their professional knowledge from memory without having access to scientific literature or other sources. In practice, knowledge integration is not (only) about dealing with different literature sources, but also about the structures of existing knowledge. For pre-service teachers, this may be the professional knowledge acquired during their university studies.

On this basis, our study aims to investigate the structures of integrated knowledge when used to analyze a pedagogical situation. We focus on pre-service teachers' professional knowledge, that they can recall from memory (not information from multiple documents) and aim to examine structures of knowledge integration. We consider the use of concept maps to be a suitable method, as they are used for representing knowledge and its structures (Pirnay-Dummer, 2020). They are graphical representations, where concepts in nodes are connected through labelled, directed arrows. Our objective is to understand the integrated knowledge base of pre-service teachers and to derive their needs for professionalization in order to develop individualized learning opportunities, because it is an important part of the use of educational sciences knowledge. We analyze pre-service teachers' concept maps, in which they reflect on a pedagogical situation, on a content and structural level. On this basis, different types of knowledge integration are identified and discussed.

In the following, we will address the paper's underlying assumptions about mental models and knowledge integration in the context of (pre-service) teachers' professional development: We do know that expert teachers have a larger knowledge base "that is organized into elaborate, integrated structures, whereas novices tend to possess less domain knowledge and a less coherent organization of it" (Ruiz-Primo, 2000, p. 32). Moreover, we assume that teachers' knowledge has a significant influence on the quality of their teaching. This assumption is underlined by findings on correlations between knowledge and teaching quality (e.g., Voss et al., 2015, for PPK; Kunter and Baumert, 2011, for PCK; and Blömeke et al., 2022, for PCK, moderated by skills and instruction quality). This indicates that there might be differences in the structures of integrated knowledge.

1.1 Coherence and knowledge integration in teacher education

In a well-integrated expert knowledge base, knowledge from different areas of professional knowledge is related. PPK includes knowledge about classroom processes, the individual learner, and heterogeneity (Voss et al., 2011). PCK "includes the knowledge of teaching and learning in a specific subject" (Zeeb et al., 2019, p. 712) like knowledge about "students' typical conceptions and learning difficulties, and about effective representations and teaching strategies, both with regard to particular topics of the subject matter" (Lehmann et al., 2020, p. 906) and is defined differently within the subjects (Ball, 2000). CK "incorporates (a) the subject matter knowledge to be taught, (b) a deeper understanding of the subject matter knowledge to be taught, and (c) an awareness and understanding of the relationships between the subject's topics included in the curriculum" (Lehmann et al., 2020, p. 906). Pre-service teachers at German universities study these areas of professional knowledge mostly separated in individual programs. There is a lack of formal-institutional coherence in Germany but also in international teacher training programs (Canrinus et al., 2019). Integrating the knowledge into a coherent overall construct as a part of professional use of educational science knowledge—informal-individual coherence (Cramer et al., 2023)—is left to the individual (Harr et al., 2014). If prospective teachers do not integrate the knowledge that is taught separatly, there is a risk that fragmented knowledge (Renkl et al., 1996) or unconnected knowledge-in-pieces (DiSessa, 2013) will emerge. This means that individual pieces of knowledge exist side by side without connection and cannot be accessed simultaneously. However, external promotion of knowledge integration through formal coherence will not necessarily lead to individual coherence, i.e., an integrated knowledge base, but requires an autonomous professionalization of the pre-service teachers (Cramer et al., 2023). Teachers of German primary science education are to be emphasized as they are teaching a subject in which knowledge from physics, chemistry and biology, among others, is taught simultaneously. Therefore, the ability to integrate knowledge seems to be of particular relevance to them.

1.2 Mental models and knowledge integration

Our work is based on the assumption that the world is represented by subjective knowledge structures called mental models (Johnson-Laird, 1983). They are "dynamic *ad hoc* constructions of individuals that provide subjective plausible explanations on the basis of restricted domain-specific information" (Ifenthaler, 2010, p. 82). A teacher thus explains a new, unfamiliar pedagogical situation using a mental model. Knowledge from various sources (e.g., information from university lectures or experiential knowledge) is used to create this model. Based on this, knowledge integration "is perceived as the dynamic process of interrelating and merging originally unconnected pieces and structures of knowledge into a common (coherent) mental model" (Lehmann, 2020, p. 11). A "mindful integration" (Rousseau and Gunia, 2016, p. 669) of information from different sources includes scientific evidence (Stark, 2017) as well as local evidence (e.g., experience or use of diagnostic tools). This is beneficial for developing an adequate and undistorted mental model (Richter and Maier, 2017). Concerning teachers, these pieces of knowledge can originate from the same or different areas of professional knowledge (CK, PCK, PPK) and can be integrated within (e.g., PPK and PPK) or across areas (e.g., PCK and PPK).

Knowledge integration can be operationalized by multiple-document learning theories (List et al., 2019). Based on the assumption that people – when reading texts – develop mental models of the contents and of the relationships between the texts, the Documents Model Framework (Perfetti et al., 1999) provides different qualitative forms of information integration. These differ depending on the relations which the reader establishes between the texts and how well the information are assigned to the original text (List et al., 2019). Ideally, relationships between the texts, e.g., contradictory or complementary aspects, are mentioned and all statements are referenced (tag-all-model, List et al., 2019). One theoretical approach to teacher professionalization that requires a certain type of integrated knowledge is the meta-reflexivity approach (Cramer et al., 2023). According to the principles of meta-reflexivity, teachers need to use multiple perspectives to reflect on pedagogical situations, but always take into account origins and boundaries of the knowledge (Cramer et al., 2023). Knowledge is integrated by relating and embedding it in different contexts. The claim of meta-reflexivity is thus an explicit and conscious integration of information within and across knowledge areas. At present, there is no operationalization of the concept of meta-reflexivity in the context of knowledge integration yet. Another theoretical approach that describes a certain type of knowledge integration is the 'knowledge restructuring through case processing' (KR-CP) theory (Boshuizen et al., 2020). In the course of developing expertise, declarative knowledge is restructured into case-based knowledge through (professional) experience. Theoretical knowledge is no longer explicitly used, but it is implicitly linked to experiential knowledge (Gruber, 2021). According to Gruber (2021), these dynamic units of knowledge contain generalized experiences and deviations from them, and both are enriched with increasing experience, enabling adaptive action. This results in a mental model in which declarative knowledge is integrated with experiential knowledge. The integration may not be explicit or verbalisable. The 'Refined Consensus Model of PCK (RCM)', which was developed for science education, represents a similar view (Carlson et al., 2019). According to Carlson et al. (2019) PCK is subdivided into three subtypes: Collective PCK (cPCK) comprises shared, declarative knowledge. This primarily includes knowledge taught at university. In contrast, personal PCK (pPCK) is a body of knowledge that "is developed, shaped, and refined over time through formal education, teaching experiences, and professional sharing. The result is a specialized knowledge and set of skills for teaching particular science topics for particular students in particular learning contexts." (Carlson et al., 2019, p. 88). Enacted PCK is knowledge selected from the corpus of pPCK in a specific situation and is translated into actions (Carlson et al., 2019). Just as in the KR-CP theory, the pPCK provides knowledge that integrates declarative and experience-based components. The integration may also not be explicable or verbalisable.

1.3 Current state of research

A considerable number of studies has been conducted on knowledge integration and its assessment. To assess structures of integrated knowledge, the mental models need to be externalized as re-representations of knowledge (Ifenthaler, 2010) for example through written text (e.g., Zeeb et al., 2020). However, the approaches and their results are heterogeneous (Lehmann et al., 2020). They differ in their operationalizations and considered knowledge areas (CK, PCK, PPK). Some studies focus on first-order knowledge integration (Lehmann et al., 2020) and operationalize processes of knowledge acquisition through the use of learning strategies (e.g., Lee and Turner, 2018; Lehmann et al., 2020). Others focus on second-order knowledge integration (Lehmann, 2020); i.e., they focus on products of knowledge application (e.g., Harr et al., 2014; Zeeb et al., 2020). Regarding the considered knowledge areas, some studies analyze knowledge integration within an area (mostly PPK, e.g., Hartmann et al., 2021, but also PCK, e.g., Stender and Brückmann, 2020) others analyze it cross-area (Zeeb et al., 2020). Moreover, sometimes PCK is defined as an independent area of knowledge (transformative model; Berry et al., 2016), sometimes as a joint use of CK and PPK (integrative model; Berry et al., 2016). For example, Janssen and Lazonder (2016) code the occurrence of PCK when PPK and CK are used together in a justification for lesson planning decisions. Research findings are therefore heterogeneous. To date, no studies have examined both integration within and cross-area simultaneously. However, it may be important to be able to consider both modes concurrently, as integrating a variety of knowledge components within and outside knowledge areas is essential in the everyday practice of teachers.

Another issue is the operationalization of knowledge integration structures. Based on the stages of expertise development (Berliner, 2004), we anticipate that various forms of integration exist. However, many studies have assessed integration dichotomously: in qualitative settings, content units are merely coded as *occurrence* or *non-occurrence* of knowledge integration. For example, Zeeb et al. (2020) analyze statements about a text scenario. Coding takes place at sentence level, and integration is coded when both PCK and PPK are used in a sentence. Graichen et al. (2019) operationalize knowledge integration through the use of information from several given texts in a sentence (referred to as coherence-building organization). Initial approaches to analyzing the quality of integration are based on rating how detailed the references to sources are. Harr et al. (2014) and Winsor et al. (2020) also describe a dichotomous operationalization: if knowledge from more than one area is used in a meaning section, then (potential) integration is coded. References to different structures of integration can be found for example in Hartmann et al. (2021). The authors differentiate between implicit and explicit forms of document integration using multiple document learning theories. Explicit integration takes place for example when information is compared. The analysis remains closely linked to the sources used, making it difficult to capture the integration structures of prior knowledge.

In summary, research to date has not yet analyzed the structures of knowledge integration simultaneously within and across the knowledge areas, and there is a lack of appropriate measurement instruments – especially when it comes to teachers' professional knowledge and not solely information newly acquired from texts. However, a detailed assessment is necessary to adapt pre-service teachers learning opportunities and to promote coherence and a professional use of evidence-based knowledge in teacher education. Pirnay-Dummer (2020) analyzes semantic microstructures of written text using the T-MITOCAR software, which creates associative networks out of the text. These networks can be used to analyze the structures of knowledge integration more differentiated with graph theoretical methods. However, the author points out, that different writing skills may distort the assessment of knowledge integration structure.

1.4 Concept maps as an assessment tool

Following on from the research of Pirnay-Dummer (2020), concept maps appear to be an adequate method of representing knowledge (integration) structures. Concept maps graphically represent knowledge and its structures (Novak and Cañas, 2008). They consist of concepts written down in nodes (in the following: vertices n), which may be connected by labelled and directed arrows (in the following: edges k). Following an associationist theory approach, there is no claim to a hierarchical arrangement of cognitive structures, and a high-quality concept map does not need to be hierarchical (Ruiz-Primo and Shavelson, 1996). A concept map is constructed by referring to a focus question, which provides a context, e.g., a pedagogical situation "that we are trying to understand through the organization of knowledge in the form of a concept map" (Novak and Cañas, 2008, p. 2). Creating a concept map can thus be classified as second-order knowledge integration. Current research on assessing knowledge structures in concept maps is very heterogeneous. Schwendimann (2019) provides a detailed description of the research situation with a focus on science learning. Existing approaches mostly analyze the integration of knowledge from a narrowly defined area of (scientific) content knowledge, e.g., photosynthesis in pupils' maps. Some approaches focus on the content and the correctness of the links in the maps (e.g., Evans and Jeong, 2023). Other approaches focus on the given structures through graph-theoretical calculations (e.g., Krabbe, 2014) or heuristic coding of the structures (Kinchin et al., 2000). Graph-theoretical measures are – among others—size (number of vertices n), complexity (number of edges k), and density (average number of edges per vertex k/n) of a concept map (Krabbe, 2014). Kinchin et al. (2000) classify three types of structure when coding a map as a whole: The type spoke (radial structure, all concepts are directly linked to the core concept) shows little complexity, and adding/removing a concept has little consequence for the overall construct. A chain (linear structure) represents a sequence where concepts are linked one after another. Adding a concept may be difficult and removing a concept can cause the entire chain to lose its meaning. The map type net shows a complex interaction between concepts, and adding/removing a concept is possible without significantly changing the given structures. "Implicit in this classification is the development of increasing integration of a conceptual framework from spoke structures towards net structures" (Kinchin et al., 2000, p. 46). Previous research has therefore either remained at the content level or analyzed the explicit structures of concept maps. A connection between content and structure level has been missing so far. This leads to our research questions:

> *Research question 1 (RQ1): What structures of knowledge integration can be found in pre-service teachers' concept maps?*

To answer this question, we analyze concept maps of pre-service teachers, in which they explain a pedagogical situation to which knowledge from all three knowledge areas can be applied. The pre-service teachers are allowed to draw upon all of their existing knowledge. We can derive different model-like expectations of the structures of integrated knowledge from the theoretical considerations on the development of expertise and the professionalization of teachers. This results in our second research question:

> *Research question 2 (RQ2): Do the identified structures of knowledge integration correspond with different theoretical models of knowledge integration structures?*

In line with these research questions, we ask on a methodological level whether the newly gained insights into possible structures of knowledge integration usefully complement the established instruments for analyzing concept maps, such as Kinchin et al.'s coding scheme (2000) or graph-theoretical calculations (Krabbe, 2014):

> *Research question 3 (RQ3): To what extent do the newly gained insights into possible structures of knowledge integration affect the previous evaluation of concept maps with conventional methods?*

2 Materials and methods

2.1 Design

Our study is a one-time cross-sectional study and exploratory in nature. It is being conducted at a medium-sized German university and involves pre-service teachers who are well advanced in their university teacher education program. The data collection took place in the context of a seminar to prepare and accompany a five-month practical phase at school. A total of 33 students ($M_{Age} = 26.6$; $SD_{Age} = 4.6$; 30 female) for primary school teaching ($n = 30$) or special education ($n = 3$) created concept maps before the beginning of the course. All participants aimed to teach the subject of primary science education (which includes the subjects biology, geography, chemistry, physics, social sciences, history and technology as a joint subject in Germany) and attended the second or third semester of their Masters' program (on average). Participation in the study was voluntary.

The participants were asked to explain a pedagogical situation in a concept map using their knowledge. We introduced them to the method of concept mapping and gave them a handout about creating a concept map, which they could access during the process. The concept map task itself consisted of the pedagogical situation and a focus question (see Table 1) to prompt knowledge integration (Lehmann, 2024). The situation describes a classroom situation from a science lesson, for the explanation of which knowledge from all three areas of knowledge was applicable. The students had 20 min to create the concept map on a blank sheet of paper. No guidelines were given

TABLE 1 Pedagogical situation and focus question of the concept map task.

Part of the task	Text for participants
Pedagogical situation	At the beginning of a lesson series in fourth grade science class, the children are given the following task: 'Draw what's inside you.' and the following instruction from the teacher: 'Afterwards, we'll compare our drawings in a circle.' The children start drawing immediately. After a short time, the student Kim begins to look at the other students' drawings, then puts down his/her own pencil and begins to cry. When the teacher asks him/her what happened, he/she says: 'I just cannot do it… I've never been good at drawing, and my mom says that some people just cannot draw. Look, the others are much better than me… I cannot do it on my own, and then I'm the outsider… and then you think I'm bad too.'
Focus question	What did the teacher want to achieve with the task and what happened in the situation described? Which didactic, subject-specific and educational science concepts can you use to analyse the situation? How are these linked to each other (if they are)?

Translated from German.

regarding the pens or colors to be used and no sources of knowledge (such as texts or access to the Internet) were provided. At the beginning and after ten minutes, the students were reminded to write down anything they could think of and use colloquial language if necessary to reduce their fear of writing down the 'wrong' knowledge.

2.2 Coding

The coding process consisted of several steps. We started with structural coding and graph-theoretical calculations. Additionally, a content coding was carried out, which consisted of three sub-steps.

For structural coding, we coded the maps according to the classification of Kinchin et al. (2000). The coding criteria were adapted to the actual data material; for example, we did not require any hierarchical structures. The material was double-coded throughout by two researchers of the team, unclear cases were discussed. On a graph-theoretical level, we determined the complexity, size and density of each map (Krabbe, 2014).

Next, the concepts in vertices were coded thematically. Each concept within a vertex was assigned to a subject area category, which in turn were assigned to the knowledge areas CK, PCK and PPK. Since coding was done concept by concept, a vertex can also contain multiple categories. The categories for PPK concepts were based on Schellenbach-Zell et al. (2023). During the coding process, these were inductively adapted, and categories were added or removed. The CK and PCK categories were created inductively based on the material. In addition, an extra category was added to include concepts that already integrate knowledge from different areas and with which an empirical separation is not possible. We added a *structure* category for vertices that only structured the map. In the third step, each concept was coded regarding the use of language. A distinction was made between colloquial and elaborated language use. We implemented this part of coding as we assume that the use of language in an elaborate manner like the explicit mention of theories, can be indicative of a conscious and explicit integration of knowledge. For the second and third step of coding, a Cohen's cappa $K = 0.94$ was achieved. Exemplary categories are shown in Table 2. After coding on a content and structural level, the concept maps were digitized with the yEd program (yWorks, 2024) as you can see in Figure 1. To this end, the codes assigned in the thematic coding were placed in the vertices. These were then connected as in the concept maps. The direction of the edges and their labeling were not represented digitally, as this had already been taken into account in the thematic coding.

3 Analysis and results

3.1 Structural patterns of knowledge integration (RQ1)

After coding the concept maps thematically and digitizing them, three distinct structural patterns emerged, each representing a unique form of integration of different concepts within and across knowledge areas as shown in Figure 2. The integration types result from the combination of structural and content-related characteristics.

The first type of knowledge integration *I Interrelation* occurs when two vertices are connected by an edge. This form reflects the type of knowledge integration, which is usually assessed by graph theoretical measures (Krabbe, 2014). It seems to be quite explicit, i.e., participants consciously related knowledge through edges. This type of integration can take place both across and within knowledge areas. This can be seen, for example, in concept map SI13. The vertex "die Ursache erforschen können" ("be able to investigate the cause," coded as 'search for causes', PPK) is connected by an edge to the vertex "psychisch" ("psychological," coded as 'physical/cognitive conditions of the students', PPK). This means that two different concepts, represented in individual vertices are explicitly connected by an edge (here within the PPK area).

The second type of knowledge integration *II Side-by-Side* occurs when several concepts are encoded in one vertex. There is a rather implicit integration of knowledge components, which were already thought of as one vertex/concept by the pre-service teachers but can still empirically be assigned to different categories by the coders. This type of integration can take place both across and within knowledge areas. For example, one vertice in concept map SI13 contains the text "mit dem Vorwissen den Lernstand der SuS überprüfen, um den nachfolgenden Unterricht zu gestalten" ("use prior knowledge to assess students' learning status in order to plan subsequent lessons"). This was coded with the concepts 'lesson planning' and 'prior knowledge/ pre-concept'. Thus, there are two different concepts in one vertice.

The third type of knowledge integration *III Merging* can be seen in concepts that cannot be empirically assigned to a single area of knowledge. It always takes place across knowledge domains and is very implicit. This applies, e.g., to all concepts of the 'prior knowledge/ pre-concepts'-category. For example, the term "Wissensabgleich" ("knowledge alignment") can be found in one vertex of the concept map SI13, which we assign to the concept 'prior knowledge/ pre-concepts'. This concept is found both as a PPK concept (it is relevant, for example, for cognitive load, Endres et al., 2023; or knowledge retrieval from long-term memory, Woolfolk and Usher, 2025) and as a PCK concept (e.g., in primary science education; Schmitt and Fellensiek, 2021). During coding, it is not possible for researchers to determine which area of knowledge it can be assigned to.

TABLE 2 Excerpts from the coding manual.

Category	Text for participants	Example (translated from German)
Motivation / regulation (PPK)	Concepts related to students' intrinsic and extrinsic motivation (and the ability to maintain it) or to measures taken to increase motivation	Tolerance of frustration
Subject-specific method (PCK)	Identification of the subject-specific method of drawing graphical representations	Drawing assignment
Subject matter (CK)	Subject-specific knowledge from one of the related disciplines	Body composition, organs
Prior knowledge / pre-concept (PPK/ PCK/CK)	Referring back to the students' prior knowledge	Activate students' prior knowledge
Use of everyday language	Description at an everyday language level	Self-confidence
Use of elaborated language	Naming of theories and professional terms	Self-efficacy

On average, 76.8% (*SD* = 7.2%) of the integrations of a concept map are interrelating integrations, 13.1% (*SD* = 10.0%) are *II Side-by-Side* integrations and 10.1% (*SD* = 7.2%) are merging integrations. Of the 33 concept maps analyzed, there is only one concept map in which only interrelating integrations occur. Six concept maps combine the types *I Interrelation* and *II Side-by-Side*, four maps contain the types *I Interrelation* and *III Merging*. All three types of integration can be found in 22 concept maps.

3.2 Correspondence with theoretical approaches (RQ2)

Since *I Interrelation* explicitly connects different knowledge components with each other, this type of integration seems to be most likely to indicate meta-reflexive knowledge integration. The explicit integration could indicate an awareness of the individual knowledge components. Individual knowledge components can easily be extracted from the integrated knowledge if necessary. Knowledge that was integrated by the more implicit types *II Side-by-Side* and *III Merging* appears to be less clearly definable and therefore less assessable in terms of foundations and limitations. But meta-reflexivity "includes reflection on the foundations and limitations of cross-conceptual perspectives, recognition of differential axiomatics, and the nature of knowledge" (Cramer et al., 2023, p. 2). At the same time, we consider the use of elaborated language to be a potential indicator of meta-reflexive knowledge integration. The use of scientific language may indicate "an awareness of one's own convictions and knowledge" (Cramer et al., 2023, p. 5), which is important from a meta-reflexive point of view. In terms of mindful integration (Rousseau and Gunia, 2016) the use of elaborate language, which may be an indication of the use of scientific knowledge (as in Schellenbach-Zell et al., 2023), is a quality criterion for an evidence-based teaching. However, it remains to be discussed whether knowledge verbalized in colloquial language can also represent scientific evidence.

In contrast, *II Side-by-Side* and *III Merging* show a more implicit form of knowledge integration. The pre-service teachers use several concepts or a concept assigned to several knowledge areas in one vertex without making an explicit connection. This could be an indication of restructured knowledge in the sense of the KR-CP Theory (Boshuizen et al., 2020) as a more practical knowledge (Li and Sang, 2023) is in focus. Experience that forms the basis for this restructuring can be acquired through practical examples during university studies or internships in the case of the pre-service teachers. Also, these structures may be in line with the Refined Consensus Model of PCK (Carlson et al., 2019) and may represent a form of pPCK that integrates declarative and experience-based knowledge components.

3.3 Additions to evaluation methods for concept maps (RQ3)

Regarding graph-theoretical measures, the range of topics, and the proportion of elaborated vertices, presented in Table 3, the concept maps show a heterogeneous appearance.

As can be seen in Table 4, 60% of the maps have a network structure, which—according to Kinchin et al. (2000) – indicates elaborate knowledge integration.

When adapting the graph theoretical measures according to the integration structures (RQ1), we can re-evaluate the density of a concept map. Up to now, the more implicit types of integration *II Side-by-Side* and *III Merging* have not been included. The equation for the density of a map is k/n (Krabbe, 2014). Concept map PR09O (Figure 3) has 15 vertices and 16 edges. The density is therefore 16/15 = 1.07. However, if the implicit types of integration are taken into account, the equation is no longer k/n, but j/n where j is the sum of all integrations of a concept map. According to the new coding, in addition to integration by edges (*I Interrelation*, 16 times), there are also integrations by *II Side-by-Side* (9) and *III Merging* (3) in PR09O. The *density(new)* is (16 + 9 + 3)/15 = 28/15 = 1.87. The density is therefore significantly higher than before when only considering *I Interrelations* as integrations.

An exemplary comparison of three concept maps (Figures 3–5) demonstrates that when analyzed solely on the basis of structure or content, as per previous assessment methods, certain aspects of integration remain imperceptible. For example, both CM11F and PR09O have been coded as a net according to Kinchin et al. (2000), and have a similar density and number of used concepts (Table 5). The differences between the concept maps only become apparent when the three types of integration are taken into account. In CM11F a significantly larger proportion of integrations takes place through explicit linking of vertices, while PR09O has significantly more implicit integrations through the use of several concepts per vertex (Table 5). In addition, CM11F has a significantly lower proportion of integrations that lie within a knowledge area than PR09O (Table 5). In PR09O, PCK concepts are not explicitly named, but can only appear in concepts that have already been integrated. The former concept map could therefore be assigned to a more meta-reflexive integration, while the latter could be characterized by KR-CP. The concept map SI13M has the greatest complexity (number of vertices) and the greatest size (number of edges) (Table 5), but other structural features,

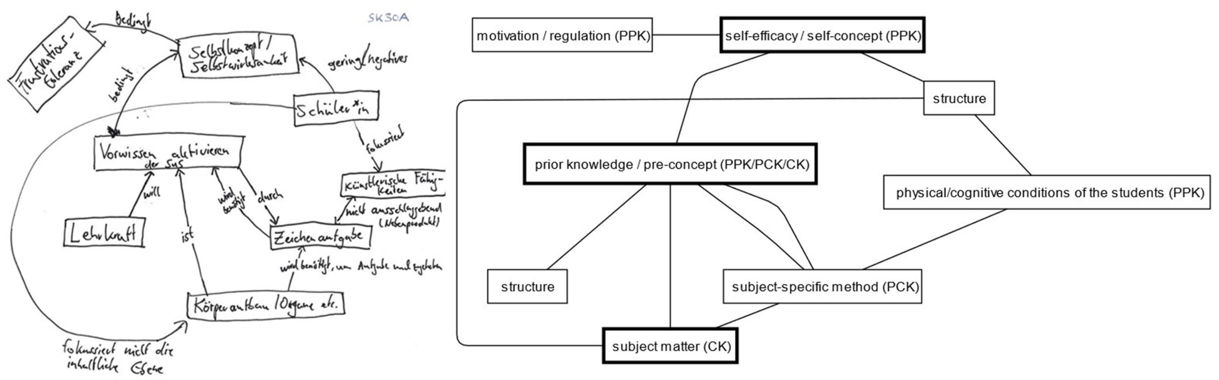

FIGURE 1
Concept map SK30A before and after coding and digitizing.

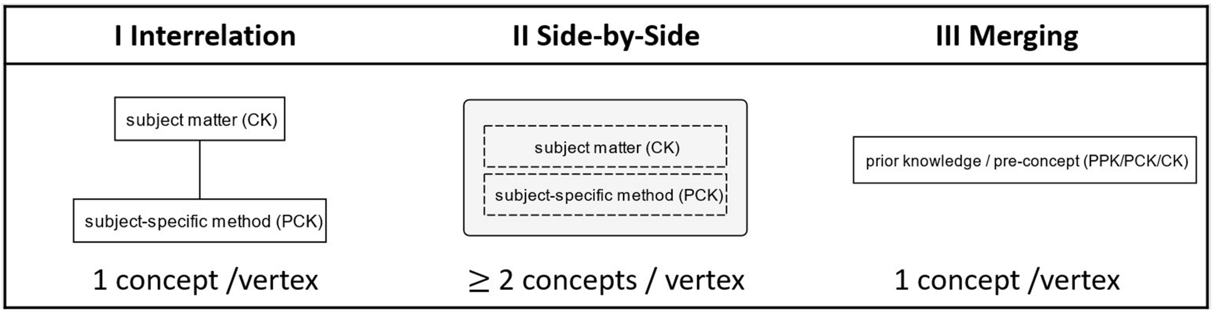

FIGURE 2
Three types of knowledge integration.

TABLE 3 Descriptive measures (n = 33).

	Average	SD	Max	Min
Size (k)	17.12	6.547	31	6
Complexity (n)	13.48	5.518	30	6
Density (k/n)	1.30	0.26	1.78	0.89
Number of different concepts	9.58	2.658	15	5
Proportion of elaborated vertices	29.15%	19.13%	66.67%	0%

TABLE 4 Structural coding (n = 33).

	Chain	Spoke	Net
Number (percentage)	3 (8.6%)	9 (25.7%)	21 (60.0%)

such as the low density and the coded spoke structure, show that the knowledge is not as well linked as in other maps. This becomes clear when compared with PR09O: despite the double number of vertices, the same number of concepts is addressed (Table 5). However, the comparison of the *density(new)*, in which both explicit and implicit integrations are taken into account, shows that SI13M has a slightly higher value than PR09O. An assessment of the integration based solely on structural or content features could therefore be misleading as knowledge integration structures are complex and their assessment varies depending on the measuring instrument used.

4 Discussion

Against the background of a mindful knowledge integration of pre-service teachers as an important part of the use of educational science knowledge, this article explores the question of which structures of knowledge integration can be captured, how they can be assigned to theoretical concepts of teacher professionalization, and whether newly developed indicators can provide added value compared to the sole use of conventional indicators. We used concept maps to capture the structures of knowledge integration of primary science education pre-service teachers and analyzed them on the basis of content-related, structural and graph theoretical characteristics. As a result, three forms of integrated knowledge *I Interrelation*, *II Side-by-Side* and *III Merging* are found. The latter two may represent a more implicit form of integration which has not been captured in concept maps to date. The forms can be assigned to the theoretical considerations regarding meta-reflexivity (Cramer et al., 2023) and knowledge restructuring through case processing (Boshuizen et al., 2020). The inclusion of these structures of integration using graph theoretical measures has an influence on the calculation of concept maps' density and thus the extent of measured knowledge integration.

Compared to the current state of research, the study presents various conceptual developments: First, the pre-service teachers of our sample do not refer to scientific texts or lectures provided but to their own knowledge when creating the concept maps. This is closer to an

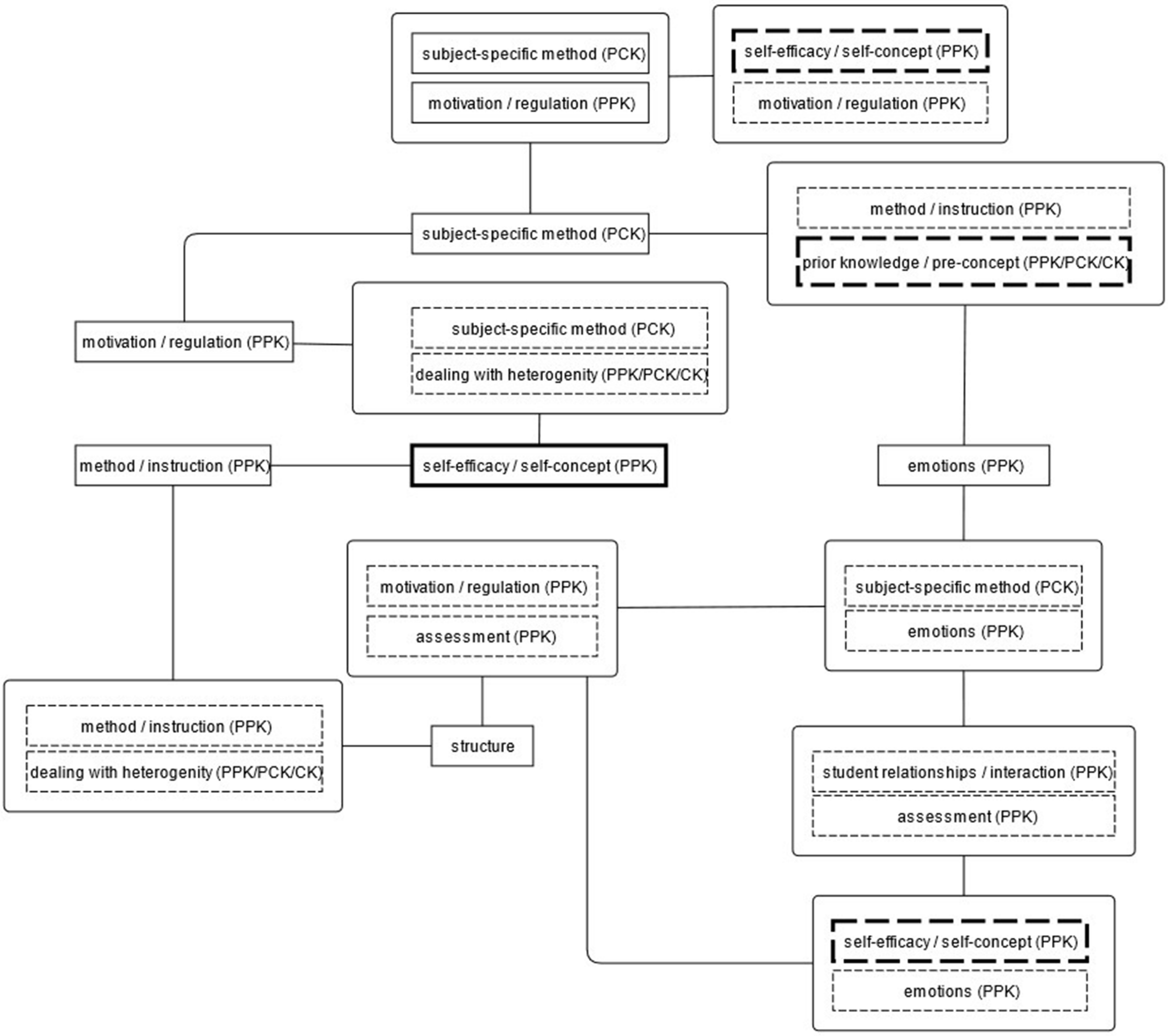

FIGURE 3
PR09O.

integration of knowledge as applied in everyday pedagogical life than analyzing text-based integration. The study does not record how information from multiple texts is integrated, but rather the actual integration of knowledge in students' mental models. This may be a relevant further development in order to approximate the actual competence of teachers in practice. Second, this study captures knowledge integration within and across the knowledge areas CK, PCK and PCK. Looking at both forms (within and across knowledge areas) tends to reflect the everyday reality of teachers. However, there has not yet been a simultaneous recording. Third, in contrast to the previous dichotomous assessment of knowledge integration, we can now analyze the structures of knowledge integration differentiated. This can be used, for example, to map the stages of expertise development (Dreyfus et al., 1987), which was previously not possible. However, only this differentiated measurement allows to provide individualized support opportunities for pre-service teachers at different stages of their expertise development. Fourth, the method of capturing knowledge integration with concept maps is expanded: through the novel use of the method more implicit forms of integration become visible. These forms have barely been recorded to date, although they might represent an important part of integrated knowledge. We also show that concept mapping is not only suitable for assessing strictly defined knowledge (such as scientific content knowledge), but also less unambiguous or clearly delineated knowledge. Fifth, we present first approaches to operationalize the theoretical concepts of meta-reflexivity and KR-CP with reference to research on knowledge integration. We assume that the process of knowledge integration and the structures of integrated knowledge could be closely related to the aforementioned professionalization concepts and could make it possible to capture a professionalization process.

4.1 Limitations and unresolved questions

All results should be considered against the limiting factors of our exploratory study, which means for example, that only one survey date

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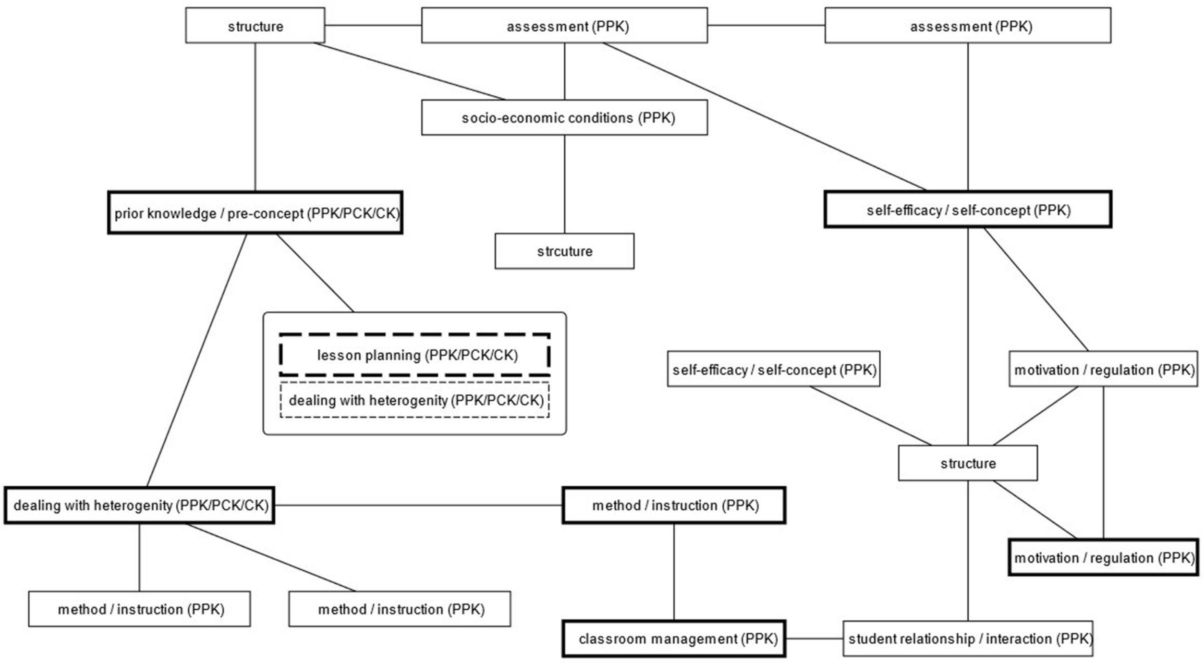

FIGURE 4
CM11F.

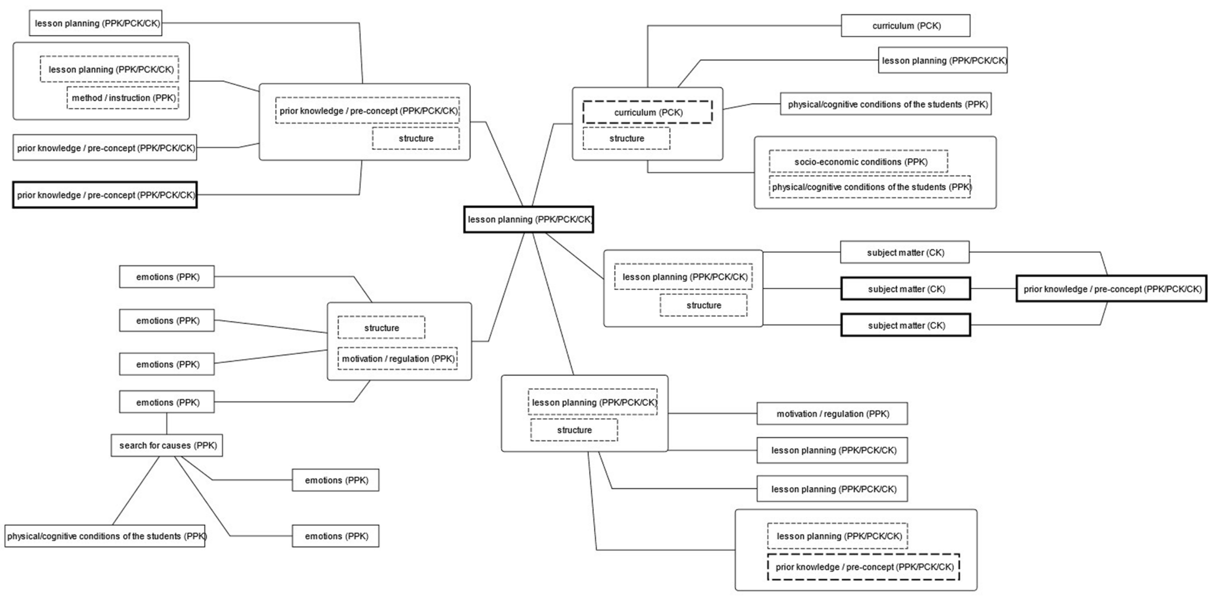

FIGURE 5
SI13M.

was considered. The study has a small and very specific sample size. This is due to the relatively small number of students enrolled in the primary science education studies program at the university where the data was collected. Only a limited number of students enter the practical phase of this program per semester. However, this is not unusual for German universities and represents a rather typical sample as studying a Master of Education is mandatory to become a teacher in Germany (for more information regarding German teacher education, see Cortina and Thames, 2013). In addition, the coding is highly inferential. Moreover, all results relate only to the knowledge about one pedagogical situation and could possibly be different for other situations. Another important limitation is that our study (and research on knowledge integration in general) analyzes representations of integrated knowledge (Ifenthaler, 2010) rather than actual structures in the brain or memory processes. This should be taken into account when interpreting the results. In addition, we use elaborated

TABLE 5 Comparison of CM11F, PR09O and SI13M.

	Structure				Content		Structure + Content						
	Complexity (n)	Size (k)	Density (k/n)	Structure (Kinchin et al., 2000)	Number of different concepts	Vertices using elaborate language (share of total number of vertices)	Total amount of integrations (j)	Density (new) (all forms of integration; j/n)	Relating Concepts (share of total integration)	Using concepts side-by-side in a vertex (share of total integration)	Using merged concepts in a vertex (share of total integration)	Integrating two or more areas (share of total integration)	Integrating within an area of knowledge (share of total integration)
CM11F	18	22	1.22	Net	12	0.39	25	1.38	0.88	0.04	0.08	0.64	0.36
PR09O	15	16	1.07	Net	10	0.27	21	1.87	0.57	0.43	0.00	0.19	0.81
SI13M	30	31	1.03	Spoke	10	0.23	45	1.5	0.69	0.07	0.24	0.22	0.78

language as an indicator of possible meta-reflexive knowledge integration. At the same time, participants were advised during the concept map creation process to also use everyday language if necessary. That is why this part of the coding has only limited informative value and should be critically revised in future studies. Nevertheless, we suspect that even in our study, the explicit mentioning of theories may provide clues as to how easily theoretical knowledge can be retrieved.

It remains open whether the three forms of knowledge integration should be considered equivalent regarding the quality of knowledge integration, or whether they should be arranged hierarchically. There are theoretical indications that an explicit integration of knowledge will benefit the professionalization of teachers if the results are placed in the context of meta-reflexivity (Cramer et al., 2023). Only a critical relation of knowledge makes it possible to understand the complex and ambiguous pedagogical everyday life and, if necessary, to develop alternative courses of action. That is why elements of knowledge should always be related to each other and assessed against the background of their context of origin, etc. in the context of meta-reflexivity. We assume that this is best reflected by *I Interrelation*, in which the concepts in vertices are explicitly connected by labelled edges. The relationship is specifically visualized and explained. Assuming that meta-reflexive knowledge integration would represent a higher quality integration than other forms, then those concept maps with high proportions of *I Interrelation* and/or high proportions of elaborated vertices would be of higher quality than other maps. Kinchin et al.'s (2000) explanations of concept map coding also contain assumptions about how a knowledge structure should look so that new knowledge components can be better inserted or old ones removed without disrupting or destroying the functionality of the structures. According to Kinchin et al. (2000), network structures are best suited for this purpose. If these considerations are transferred to individual integrations of a concept map, then here, too, *I Interrelation* appears to be the form of integration in which it is easiest to adapt or supplement connections. Integrations that take place within a vertex, on the other hand, appear to be more stable and less easy to detach or change. In contrast, research shows that the teaching of already integrated knowledge promotes the knowledge integration of student teachers (Harr et al., 2014). It could be assumed that teaching integrated knowledge results in such rather implicit integrations as *II Side-by-Side* and *III Merging*; as Lehmann (2024) indicates that there is a connection between the integration processes and the application of integrated knowledge. In addition, both characteristics could indicate knowledge integration with case-based knowledge resulting from knowledge restructuring (Boshuizen et al., 2020) or pPCK (Carlson et al., 2019).

The following questions, among others, remain unresolved to date: Can the types be classified as explicit and implicit forms of integration? How aware are the pre-service teachers of integration, and can they answer elaborately when asked? How flexibly can new knowledge be integrated or the model be adapted to other situations? Do the pre-service teachers only use university knowledge, or is case-based experiential knowledge also integrated? Does the type of integration structures used have an influence on actual action in pedagogical practice? How and whether do the concept maps change over the course of the participants' professional careers (do they possibly reflect stages of expertise development)?

So far, this study has distinguished between knowledge from different areas (CK, PCK, PPK) in its coding, but it has not focused on the distributions in which students refer to knowledge from these areas. However, this could be an interesting consideration for further studies: In what types of situations is one area of knowledge used more than the others, and when are they all used equally? Does it make sense to encourage pre-service teachers to use all areas of knowledge equally, or is it sufficient to set different priorities in different situations? What the results of Molitor et al. (2025) might indicate is that comprehensive coverage of all three areas of knowledge at this stage of professionalization may still be too demanding for pre-service teachers.

Additional research is necessary to further elaborate on the characteristics of the three types of knowledge integration and to answer the unresolved questions, e.g., through retrospective interviews with the creators of the concept maps. Alternatively, think-aloud protocols could be recorded to obtain process data. Molitor et al. (2025), for example, examined think-aloud protocols (of pre-service teachers writing a reflective essay about a pedagogical situation) with regard to the application of information-processing epistemic processes. It might be useful to conduct a similar study focusing on the use of knowledge-integrating epistemic processes. It can be further elaborated how much case-based knowledge is already integrated by pre service teachers, or how aware they are of the origin and limits of the knowledge used. In this way, the classification of the structures into certain forms of knowledge integration can be validated or improved. The question of the hierarchy of the various structures could also be examined more closely.

In addition, studies could be conducted with other situational vignettes and variable samples (e.g., pre-service teachers from other universities or subjects). All qualitative results could then be validated by quantitative studies in experimental settings. Moreover, it could be useful for future studies to expand the sample to include experts, i.e., experienced teachers, and to conduct an experimental comparison of the integration structures of novices and experts, given that experts have a better-connected knowledge base than novices (Ruiz-Primo, 2000). This could provide insight into the development of integrated knowledge with regard to different stages of expertise (Berliner, 2004).

5 Conclusion

However, the findings of this study can already be used to analyze the abilities and, above all, the problems of knowledge integration (and thus one part of the use of educational science knowledge) of pre-service teachers. It is possible to find out which forms of integration pre-service teachers have already mastered (implicit vs. explicit; within or across knowledge areas) and which still need to be specifically promoted in university teacher education. Concept maps could also be used to analyze which knowledge the pre-service teachers can apply to a specific pedagogical situation and which knowledge is still completely lacking or solely exists as inert knowledge (Renkl et al., 1996). The promotion of knowledge integration is relevant for all pre-service teachers, but especially for those who aim to teach primary science education, as the institutional-formal coherence in the degree program is less than in other teacher training programs due to the combination of many different subjects.

In conclusion, this study contributes to a better understanding of the structures of integrated knowledge. These findings could be used to adapt teacher training in terms of knowledge integration to the individual needs of pre-service teachers, depending on the level of expertise development.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

Ethical approval was not required for the studies involving humans because according to the German legislation on research involving human subjects, ethical approval is only required when sensitive data are collected, when physical interventions are performed, or when subjects could be harmed. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

A-LM: Formal analysis, Methodology, Conceptualization, Writing – original draft, Investigation. JS: Writing – review & editing, Formal analysis. UH: Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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