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How structure-mapping can improve K-12 education

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Abstract
Comparisons are commonplace in children's learning and in K-12 education, but teachers are given limited guidance in how best to support students' comparisons to lead to the strong learning outcomes. Structure mapping theory offers a well-articulated, evidence-based account of how people carry out comparisons and learn from them. The present article reviews this evidence and highlights ways best practices identified in the structure mapping literature can be used to improve student learning in the K-12 classroom.

Teaching is full of challenges. For example, an elementary teacher may find that their students—even those who have mastered a new mathematics procedure—cannot see how a new problem might be solved in the same way. Or a high school science teacher who has carefully designed lessons on heat flow with well-chosen concrete examples, may find that their students do not see how the examples are related. Both cases illustrate a failure to compare—either the students saw no basis for comparing across the examples, or they attempted a comparison but could not see it through. What can be done to address such challenges?

In this paper, we identify specific steps teachers can take to increase relational reasoning skill in their students, based on psychological research that reveals the mechanisms underlying the comparison process. We focus here on one particular framework for understanding comparisons—namely, structure-mapping theory—because it has a rich, empirical basis and clear implications for education and student learning. However, as we will see, this framework is broadly consistent with other frameworks in both the analogical reasoning literature and foundational education theory. We also provide examples drawn from science, technology, engineering and mathematics (STEM) teaching to illustrate how these mechanisms might be engaged in classroom teaching, while also recognizing that the same mechanisms likely underlie learning in many domains, including reading, social studies, and the arts.

1 The role of comparisons in learning

Children are asked to make comparisons throughout the day in most K-12 classrooms [54, 56, 61], and for good reason. Research shows that comparing examples of the same phenomenon can lead to substantially better understanding in a domain [2, 29, 46, 55, 59, 63, 69, 105, 106–108, 117]. For example, middle school students learned more about the structure of the solar system when they were helped to compare and align a physical model of the sun and earth with their own experience [67].

Beyond promoting the learning of specific domains, comparison practice may also foster better thinking skills. Many experts believe that activities requiring comparison, such as comparing-and-contrasting examples, making meaningful groupings, and interpreting analogies, are the backbone of higher-order thinking [1, 40–41, 57, 104]. Comparisons are integral at all levels of learning and cognitive growth. Analyses of professional discourse in scientific fields provide many examples of reasoning by comparison (e.g., [6, 14, 44, 115]) (see [25] for a review).

Activities that foster better relational reasoning have long-term benefits. Individuals with better relational reasoning skills have better academic outcomes [7, 9, 20, 58, 71], and adults with better relational reasoning skills perform better on the job across a range of professions such as engineering, nursing, counseling, educational administration, and business management [28, 32, 35, 75]. Across these varied professions, people likely perform many comparisons every day—nurses might look for similarities in symptoms to diagnose an ailment in a new patient, or engineers might recall and apply strategies that helped them solve previous problems in a new situation—so it makes sense that people with better relational reasoning skills would excel.

Conversely, those who fail to grasp relational structures struggle in school and in the world of work. They frequently default to rote procedures, seemingly unable to employ the flexible, creative problem-solving skills educators hope to foster [85, 98]. This pattern of relying on surface-level, rote learning rather than achieving deep structural understanding has been demonstrated repeatedly in research across a wide range of age groups and curricular subjects, including mathematics [8, 36], science [15, 97, 110], literacy [10, 34, 79], and computer programming [109].

Consistent with these findings, current curriculum guidelines across subject areas acknowledge the centrality of relational reasoning and call for teachers to encourage abstraction of deep relational structures [94–96]. Indeed, research tells us few student learners automatically find deep relational structures without help [2, 38, 50, 104]. Thus, the role of the teacher in supporting learners as they make specific comparisons, as well as developing generalized relational reasoning skills, is crucial. Yet, teachers are given very little guidance in how best to support students' comparisons. One might reasonably ask, then, how well are we doing at leveraging and fostering relational reasoning in schools? And what can we do to improve these efforts?

2 Structure-mapping theory

The need to encourage learning at a deep conceptual level has been recognized for decades [85]; however, whereas this need is widely recognized, the existing education literature may lack specificity in terms of its underlying cognition. In short, how do comparisons happen? Structure-mapping theory provides a precise, mechanistic account of the comparison process and how it leads to deep relational learning [30–31, 37, 41, 45]. Indeed, structure-mapping is widely accepted as a key psychological mechanism by which complex concepts are discovered and consolidated [11, 56, 76, 101, 104]. Decades of cognitive science research have revealed the optimal conditions for structure-mapping to occur (outlined in Table 1), and this knowledgebase provides a solid framework that could help classroom teachers to implement comparisons effectively.

Structure-mapping is engaged whenever one entity is compared or aligned with another—as when making analogies, comparing examples, applying a solution from one case to another, using a diagram to understand a text, or assimilating new information to an existing schema in the Piagetian sense. Comparison can be initiated by an instructor (e.g., "See how these are alike?" or "Which one is stronger?"), or by children's own spontaneous noticing of commonalities [49]. However, especially early in learning, learners are far more likely to detect similarity when the two examples share concrete surface features such as shape and color. This phenomenon explains why novice learners often fare better when the items being compared share at least a few surface similarities (e.g., color, shape, etc.) [45, 52].

An advantage of comparison for learning is that learners do not have to know the underlying structure in advance; the comparison process itself can reveal common relational patterns [16, 23, 50]. Structure-mapping highlights common relations, such as the similarity between the shapes of bird wings and airplane wings. Structure-mapping also helps learners notice patterns that have explanatory power, such as why the shapes of bird wings and airplane wings allow both entities to take flight [21, 38, 40–41, 43, 66, 73].

Table 1 Six best practices to support structure-mapping

Best practice	Evidence	Sample technique
(1) Explicitly prompt students to compare and seek commonalities	If examples are not perceptually similar, students often fail to compare them without explicit prompts [4, 16, 45, 50, 57, 67, 68].	Ask how two shapes are the same or different
(2) Promote relational alignment	Learners find points of alignment more readily when examples are simultaneously available and spatially aligned (e.g., [62, 78, 83, 84, 86, 117, 121]). (See Fig. 3.)	Offer illustrations of both examples that are at similar levels of detail or context, side by side (e.g., a bird in its habitat and a snake in its habitat).
(3) Highlight corresponding points of alignment	Learners can be guided towards points of alignment with verbal labels, gestures, and visual cues [3, 5, 16, 67, 68, 86, 114, 117, 120].	Point out the fuel tank in two different engines.
(4) Name aligned relations or state the common principles	Verbalizations direct attention to key common structures, promote retention and transfer, and support abstraction [2, 42, 51, 55, 78, 80, 117].	After children have compared two patterns (e.g., car-truck-car-truck vs. bee-flower-bee-flower), teach them the label "AB" and practice labeling the elements in both patterns.
(5) Encourage elaborations of an established mapping	Comparisons can be deepened and expanded by stating further inferences [17, 57], noting key differences [46, 48, 65, 82, 108, 117], or extending the analogy to a new case [81].	After discovering that kangaroos and koalas are both marsupials, ask students to guess what these animals' offspring might have in common.
(6) Present examples in order, using progressive alignment	Though low-similarity comparisons can result in greater abstraction, beginning learners may fail to align them, and therefore learn nothing. In this case, progressive alignment—starting with a concrete, high-similarity comparison and moving to less similar comparisons—can be effective (See Fig. 4) [18, 19, 33, 42, 47, 74, 114].	To discover how a heart is like a pump, first ask students to compare two pumps before comparing the pumps to a heart.

As more points of alignment are discovered and compared, more relational structure emerges.

Figure 1 presents a structure-mapping example from science education that shows how the processes of comparing and aligning can reveal relational systems—in this case, the convection system within the Earth's mantle. The lava lamp provides a helpful analogue because its heat source (a light bulb) causes the lava to become hotter and expand, eventually becoming less dense than the water surrounding it so that it begins to rise. Once the lava is far from the light bulb, it cools, regains density, and begins to sink, where the cycle then repeats itself. As shown in the figure, the Earth's mantle is comprised of parallel elements engaged in similar relations, noted by the solid arrows. Thus, comparing and aligning the lava lamp to the Earth's mantle reveals common relational systems and invites new inferences.

In addition to highlighting similarities, structure-mapping also highlights specific differences [39, 48]. For example, Sagi et al. [111] found adults were faster to say that two pictures were different in a low similarity comparison, such as the trees pictured at the bottom of Fig. 2, but they were faster to say *how* the pictures differed in a high similarity comparison, like the trees pictured at the top of Fig. 2. This is because the high-similarity comparison was readily aligned, leading to 'popout' of specific featural differences. Indeed, structure-mapping can be used to target important dissimilarities, because learners are more likely to notice differences that can be mapped (i.e., *alignable differences*) then they are to notice differences that are unrelated to the mapping (i.e., *non-alignable differences*) [82]. This principle can be used to help children learn critical features via comparison [46].

Research shows that structure-mapping has direct effects on learning. After people complete structure-mapping comparisons, (1) shared structures become more obvious to them [16, 73, 82] and (2) shared structures are more likely to be retained and transferred [21, 42, 53, 67]. Structure-mapping also leads to long-term gains by promoting

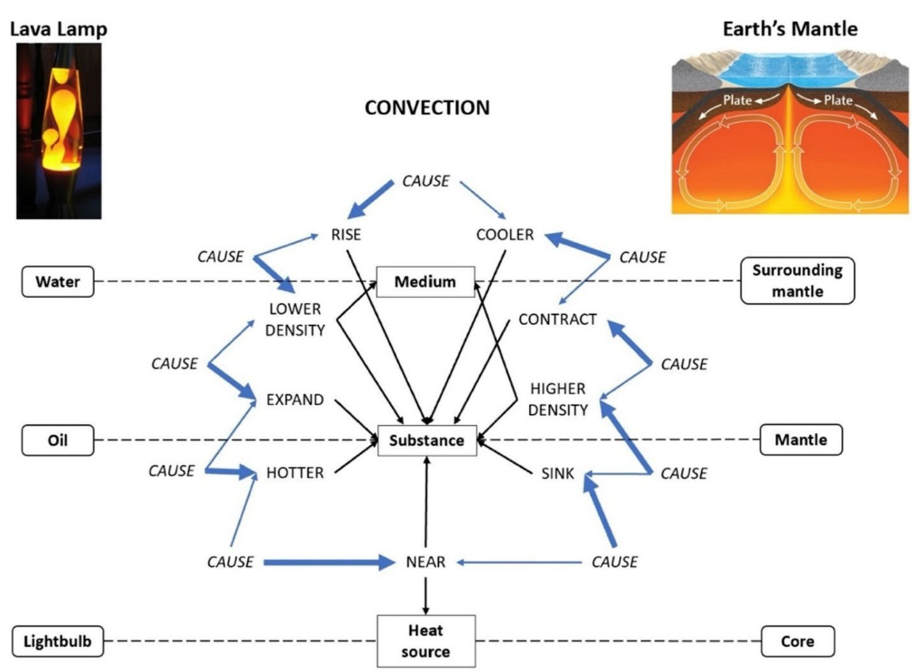

Fig. 1 How people map the shared structure between a lava lamp and the Earth's mantle

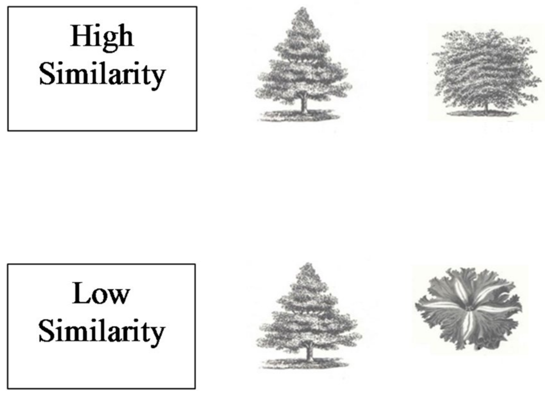

Fig. 2 High similarity and low similarity comparisons [111]

abstraction. For example, college students often fail to recognize important causal patterns such as *positive feedback* in situations such as polar ice cap melting and audio feedback [110][1]. However, when learners are asked to compare and align these two examples, they are substantially more likely to discover the common *positive feedback* relational structure. Further, they can then transfer this understanding to other examples [55].

Structure-mapping also promotes the projection of inferences from one example to the other [17, 23, 77, 91]. For example, comparing sound waves to ripples in a pond can help students imagine the effects of reflection for sound waves. Finally, as noted above, structure-mapping highlights differences in the shared relational structure (i.e., *alignable differences*) which help learners identify key distinctions, such as the difference between positive and negative feedback loops or between a fault and a fracture in geology [46, 55, 69].

Laboratory-based experiments have demonstrated that children learn from relational comparisons across the lifespan from early childhood to adulthood [16–17, 22–24, 47, 80, 93, 111]. Fewer studies have examined structure-mapping in educational settings, but the results so far are encouraging (e.g., [112]). Investigators have found that structure-mapping comparisons promote conceptual growth in science and engineering in elementary-aged children visiting a science museum [46, 68, 116], place-value concepts in kindergarten students at a low-SES elementary school [88], equation solving among middle-school students [107], and concept learning in undergraduate and graduate students [21, 73].

3 Best practices to support students' comparisons

Experimental research has demonstrated that certain conditions support structure-mapping better than others, and these conditions may be necessary for learning to occur during comparisons. In Table 1, we summarize six best practices based on a review of research directly testing structure-mapping theory, but these recommendations are consistent with those offered by other experts on relational reasoning (e.g., [27, 57, 86, 117]), as well as past work on scaffolding student learning more broadly (e.g., [119]). For example, instructional scaffolding theory highlights the value of directing students' attention to make a particular skill or task more tractable. Several of the best practices identified

[1] In the case of the polar ice cap, when ice melts, the resulting water absorbs more heat, causing temperatures to rise and melt more ice. In the case of the microphone, when audio feedback from a speaker is picked up by a microphone, the noise creates louder feedback, and so on.

below direct student attention through spatial alignment, labels, or gestures. As noted above, the evidence for structure-mapping is nearly all laboratory-based, meaning that researchers teach children individually or in small groups, either in a research lab or a quiet area of a school. Although these studies do not involve the same classroom management demands that teachers face in their daily teaching practice, they provide reason to expect that teachers who follow these best practices will have greater success, not only when conveying complex relational material to students, but also in helping students improve their relational reasoning skills more generally.

That said, we are not aware of classroom studies directly testing whether students have better learning outcomes when teachers adhere to the best practices for scaffolding comparisons identified in laboratory research. As we will see, teachers differ in their ability to support comparisons without being given specific training, but it is unknown whether these differences impact student learning [105]. Evidence of such causal effects is emerging in research on the home environment, but at a less granular level. For example, Silvey et al. [113] showed that preschool children are more likely to generate specific comparisons when their parents have frequently commented about general comparisons. There is a clear need for more detailed investigations of teacher and parent supports for comparisons and the effects of these supports, as we note below. Nonetheless, the existing literature provides abundant evidence that learners fare better when comparisons are supported in the specific ways noted in Table 1, and this information is likely applicable to teaching practice, as others have argued [57, 104]. Our goal is to expand and update these practices and illustrate in detail how they might be applied in a mathematics lesson.

To illustrate how these principles might be applied in the K-12 classroom, consider the following lesson that was used effectively to teach kindergarten students about place value [88]. Over many weeks of instruction, children progressed from simple, high similarity mappings (e.g., holding up their ten fingers to stand for "ten" and mapping their own fingers to the teacher's and classmates' fingers that were also used to stand for "ten"), to more complex, low similarity mappings, as depicted in Fig. 4 (Best Practice #6). Here, we see the quantity twenty-five represented using two different materials—base-ten blocks and dried beans in cups—as well as the written numeral, "25," (Best Practice #2). In this lesson, children were first shown the representation constructed with base-ten blocks along with the written numerals, and asked to help the teacher construct an equivalent set of beans to match (Best Practice #1). Once the beans representation had been assembled, the teacher presented all three representations together, with all three analogs spatially aligned as shown in Fig. 3 (Best Practice #2). That is, the two tens from one material (i.e., beans in cups) were in direct spatial alignment with the collections of two tens in the other material (i.e., base-ten blocks); and both materials were aligned with the written numeral "25" below them. Thus, the two tens in each example were directly aligned with the numeral "2" in the tens place, and the five ones were directly aligned with the numeral "5" in the ones place. Then, the teacher said, "Let's see if we have the same number. How can we check?" (Best Practice #1). Next, she demonstrated how to compare the examples with one another, providing verbal labels and gestures to highlight the mapping from one representation to the others—e.g., "Look, we have ten here and ten here (*while pointing to the first tens blocks and the first cup of beans*). We have another ten here and ten here (*while pointing to the second tens blocks*

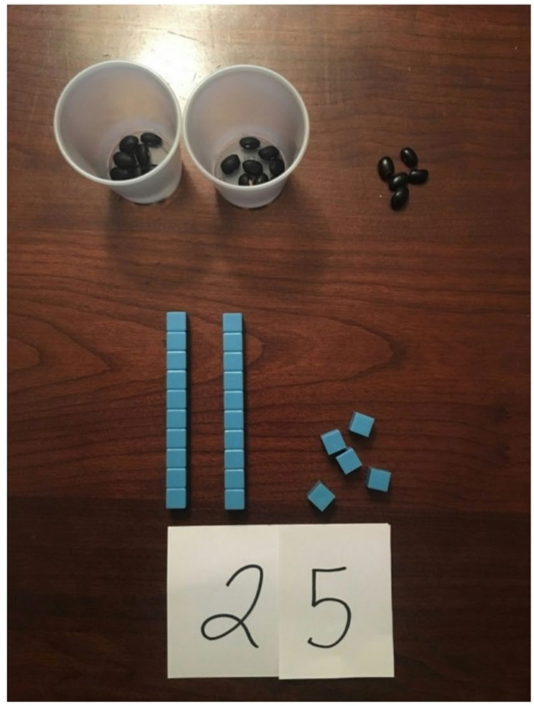

Fig. 3 Structural alignment in a place value lesson [88]

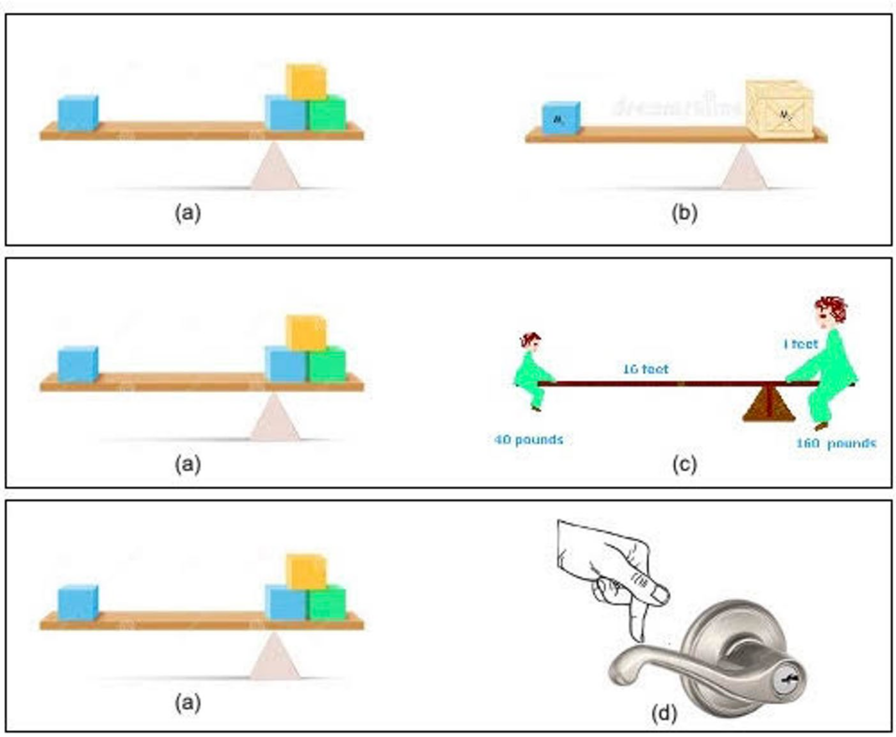

Fig. 4 Graphic depiction of progressive alignment in comparisons

and the second cup of beans). That's two tens here, and two tens here. And see? We have the number 20 at underneath. It has a two for two tens! [*and so on*] Yes, they have the same number!" (Best Practices #3, and #4). Though not tested directly in this lesson, Best Practice #5 could have been incorporated by asking children to complete the mapping process after the teacher had shown how to compare the tens.

These best practices highlight specific aspects of the structure-mapping process that teachers can leverage, but at a more general level, they also work together to allow learners to focus on deconstructing the comparison and mining it thoroughly for alignable similarities and alignable differences. With the sheer amount of content teachers are required to present in a day, it may be difficult to move through comparisons slowly enough to ensure that learners have fully grasped their meaning. However, if we have learned anything from research on analogical learning, it is that students often need time and support to fully process comparisons. When comparisons are presented in passing as brief illustrations, or if too many comparisons are introduced in rapid succession, learners may not benefit and indeed, are more likely to become confused [105].

4 Current use of structure-mapping in schools

A key question is to what extent teachers already skillfully support student comparisons, and where there may be gaps in this support. Unfortunately, structure-mapping theory and other research on comparison processes are not generally included in teacher training. For example, in a recent review of mathematics curricula, Mix and colleagues concluded that although curriculum developers repeatedly mentioned the importance of relational comparisons, they did not typically explain the *mechanics* of making comparisons and relational learning [90], thus offering no guidance about what constitutes effective instruction that leverages these processes.

Despite this lack of support, there is evidence that some K-12 teachers have discovered some of the best practices through their own extensive experience. For example, Richland et al. [103] reported that when students misunderstood a concept being taught, teachers sometimes used closer analogs to help them—an instructional move that is consistent with the practice of progressive alignment (Best Practice #6). Teachers also tend to use more gestures when they are addressing student misunderstandings, consistent with the practice of highlighting common points through gestures (Best Practice #3). Indeed, one might argue that such classroom practices partly explain the evidence that children who attend school regularly perform better on tests of intelligence [12], including tests of nonverbal reasoning such as matrix reasoning, series completion, analogies, and visuospatial reasoning, which are primarily relational reasoning tests (see [99], for a meta-analysis). Consistent with this notion, research comparing schooled and unschooled adults shows a significant long-term effect of schooling on the development of relational reasoning—which also suggests teachers have a positive impact [13].

However, given the lack of institutional guidance, it is not surprising that teachers sometimes miss opportunities to implement the best practices identified above. For example, in a recent study, preservice teachers incorrectly predicted that children would learn better from sequentially presented illustrations of mitosis and meiosis than from simultaneous presentation (i.e., presentation that would invite structure-mapping) [60]. Further, in a cross-cultural study of eighth-grade mathematics teaching, Richland et al. [103] found that American teachers were less likely than teachers from Hong Kong or

Japan to provide adequate support for understanding comparisons, such as using spatial or gestural cues to highlight points of correspondence (Best Practice #2). Richland et al. [105] also reported that teachers (1) usually made comparisons themselves and presented them as illustrations, rather than inviting students to engage in comparisons while scaffolding them in the mapping process; (2) tended to use comparisons when teaching concepts but not when teaching problem-solving procedures, leaving students to figure out how the two are connected; and (3) often provided comparisons with low surface similarity, which less advanced students may fail to align, resulting in failure to learn. Taken together, there appear to be gaps between how teachers use comparisons in the classroom and what cognitive science research tells us would be effective teaching practice. However, it is impressive that teachers have generated some supportive practices without access to this critical information, and it is likely whatever gaps exist in teachers' understanding of comparisons could be easily addressed by including structure-mapping theory in teacher training programs.

Providing explicit guidance for teachers in how best to support comparison is all the more important given the challenges teachers face when dealing with diverse classes and the demands of classroom management and typical curricula. As it stands, curricular materials themselves often fail to explicate fully how best to help children make effective comparisons, as Mix et al.'s [89, 90] review of mathematics curricula showed. It would be helpful for researchers to examine not only what teachers already know about promoting analogical comparisons, but also what logistical challenges might interfere with application of these skills in real-world classroom contexts.

Skillful support of comparisons might have far-ranging effects on student learning. One possible impact is that students will show stronger performance on tests of content-knowledge. In this case, the teacher's more skillful support of comparisons might help children fully understand examples, grasp higher-order relations, and incorporate new information into their conceptual structures. However, a second, equally important impact could be that students will show stronger performance on tests of analogical reasoning. In this case, the teacher's modelling of structure-mapping as an approach to performing and interpreting comparisons (e.g., as described by [119]) could help students learn and apply structure-mapping in their unsupervised learning. Researchers often use challenging analogical problems, such as comparisons involving cross-mapping to assess structure-mapping skill. For example, children might be asked to match the smallest of three toy houses in one array (tiny-small-medium) to the smallest of three toy houses in another array (small-medium-large), thereby pitting surface similarity (small-small) against relational similarity (small-tiny). Broader measures of analogical skill such as those used in published test batteries (e.g., the Similarities subtest from the Wechsler Intelligence Scale for Children-V or WISC-V) or developed for use with adults (e.g., Dumas and Alexander's, [26], *Test of Relational Reasoning* or *TORR*) could be used for student assessment.

5 Next steps

Our review of the literature suggests that more research is needed to understand current teaching practices for reasoning from comparisons; however, we already know a great deal about how people make comparisons from extensive research in cognitive science, and structure-mapping in particular. Given the ubiquity of relational reasoning in academic subjects, and in later career success and intellectual achievement, it is crucial to help students not only learn from comparisons but also become skillful relational learners more generally. We have suggested a framework for implementing best practices that could be included in teacher professional development and training for preservice teachers—namely, the structure-mapping approach. It would be helpful for school district curriculum experts and instructional coaches to become knowledgeable about the mechanisms of relational learning and practices that best support these mechanisms, so they can target relational learning in their coaching activities for teachers. Though many teachers may already be utilizing effective instructional practices to support learning from comparisons, they may not feel at liberty to take the time these practices require unless they receive explicit acknowledgement and encouragement. Some teachers may also lack a mechanistic understanding of why these practices are beneficial and how to optimize them. In areas where teachers are not utilizing effective practices, a clear understanding of how relational learning happens can help them find creative ways to boost relational learning throughout the day, rather than relying on curricula that may have relational learning "baked in," but which leave the mechanisms of learning unexplained (e.g., see [89, 90] for an example) As we have seen in this brief review, research on relational learning, and structure-mapping in particular, offers vast untapped potential to improve student learning, but to take full advantage, teachers need access to this information. Our hope is that the present article takes a step in that direction.

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Data availability
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