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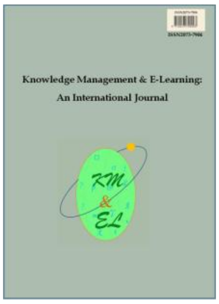

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Concept maps as versatile tools to integrate complex ideas: From kindergarten to higher and professional education

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Abstract: Knowledge is getting increasingly more complex. Learners, from Kindergarten to higher education, require powerful tools to connect complex ideas. This paper explores the range of studies that investigated concept maps as learning, metacognitive, collaborative, and assessment tools to support integrating complex ideas. Research suggests that concept maps can be successfully implemented in a wide variety of settings, from K12 to higher and professional education. However, the effectiveness of concept maps depends on different factors, such as concept map training and choosing a suitable form of concept map to match the task and learner. Developing proficiency in concept mapping takes time and practice and should not be first introduced in higher education. Concept map training could start as early as Kindergarten and include concept map generation, interpretation, and revision. This paper concludes that, if implemented thoughtfully, concept maps can be versatile tools to support knowledge integration processes towards a deeper understanding of the relations and structures of complex ideas and facilitate life-long learning.

Keywords: Concept map; Lifelong learning; Higher education; K12 education; Assessment tool; Learning tool; Metacognitive tool; Collaborative tool; STEM

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1. Introduction

As the amount and complexity of knowledge increases at an unprecedented pace (Barnett, 2000), educators and students at institutes of higher education require powerful tools that support integrating complex ideas. Higher education aims to prepare students not only to learn existing knowledge but also to generate new knowledge and to adaptively apply knowledge in complex problem spaces.

Making sense of complex problems requires connecting ideas and eliciting relations between ideas. Sense-making refers to the processes of creating a structure of related ideas, such as placing "items into frameworks" (Weick, 1995, p. 6) and continually seeking "to understand connections" (Klein, Moon, & Hoffman, 2006, p. 71) that allow solving authentic complex problems. When trying to make sense of ideas, learners of all ages, from young children to adults, hold a rich repertoire of dynamically connected, co-existing, and often conflicting alternative ideas about the world around them (Slotta, Chi, & Joram, 1995; Davis, 2000; Linn, 2002; Davis, 2003; Songer, 2006; diSessa, 2008) rather than a consistent understanding. Conflicting alternative ideas can co-exist because they are often contextualized (Davis, 2004). Consequentially, students often fail to connect ideas from one context to another (diSessa & Sherin, 1988). Prior ideas are not simply exchanged for new ideas because ideas are embedded in a dynamic network where they define and constrain each other (Demastes, Good, & Peebles, 1995; diSessa, 2008; Park, 2007). Research suggests that in order to form more integrated knowledge, learners need to add and distinguish new ideas and connections to their existing repertoire of ideas rather than replace existing ideas (Strike & Posner, 1992; Demastes, Good, & Peebles, 1995; Linn, 2008). Instead of seeing existing ideas as obstacles that need to be replaced, knowledge integration seeks to add new ideas, and through application in different contexts, help learners develop criteria to distinguish which and when ideas are relevant (Linn, 2008).

To facilitate knowledge integration processes, concept maps can serve as tools to elicit relations between ideas within and across contexts. Concept maps can be defined as a form of node-link diagram for organizing and representing semantic relations among ideas. Like other node-link diagrams, concept maps consist of visuo-spatially arranged nodes and links, but additionally they also present semantic information in the form of link labels. A concept map consists of nodes (ideas/concepts), directional linking lines, and linking labels that describe the relation between nodes. Two nodes connected with a labeled line are called a proposition (Cañas et al., 2003).

Concept maps have been implemented in higher education (for example, Trowbridge & Wandersee, 1994; Santhanam, Leach, & Dawson, 1998; Kinchin, De-Leij, & Hay, 2005; Mintzes & Quinn, 2007). However, despite such promising instantiations, concept maps are still not widely implemented as learning and assessment tools (Kinchin, 2001). Becoming a proficient concept mapper takes time and practice and should start much earlier in a student's career and in a range of different contexts.

This paper aims to provide educators and researchers with a structured overview of research on concept mapping as learning and assessment tools implemented with students from Kindergarten to higher education. The review focuses particularly on science education as an example where concept maps can be used as tools for integrating complex ideas.

The overview presented in this paper aims to answer three practical questions: In which age group can concept maps be implemented? What can concept maps be used for? In which science subjects can concept maps be implemented?

2. Concept maps and knowledge integration

To make sense of complex ideas, learners need to connect and distinguish ideas. 'Knowledge Integration' describes learning as the process of integrating ideas through the cognitive processes of eliciting, adding, connecting, critiquing, distinguishing, sorting out, refining and applying ideas in a broad range of contexts (Bransford, Brown, & Crocking, 2000; Linn & Eylon, 2006).

Concept mapping activities align well with the processes of knowledge integration as they focus on eliciting existing ideas and connections through the process of visualizing them as nodes and links (see table 1). The explicitness and compactness of concept maps can help keeping a big picture overview (Kommers & Lanzing, 1997). The 'gestalt effect' of concept maps allows viewing many ideas at once, increasing the probability of identifying gaps and making new connections. Generating concept maps requires learners to represent ideas in a new form which can pose desirable difficulties (Bjork & Linn, 2006; Linn, Chang, Chiu, Zhang, & McElhaney, 2010) - a condition that introduces difficulties for the learner to slow down the rate of learning and enhance long-term learning outcomes, retention and transfer. The process of translating ideas from texts and images to a node-link format may foster deeper reflection about ideas and their connections (Weinstein & Mayer, 1983) and prevent rote memorization (Scaife & Rogers, 1996). Throughout a curriculum, learners can add new ideas to their existing concept map. Unlike textbooks, concept maps have no fixed order and may thereby encourage knowledge integration strategies. For example, a student may decide to add the most important or most central idea first. Developing criteria to select ideas requires deeper processing than the student might normally exercise when reading text. Students need to develop meta-cognitive strategies to distinguish alternative ideas, for example through predicting outcomes and explanation generation (Bransford, Brown, & Crocking, 2000). The scaffolded process of adding and revising concept maps requires students to decide which ideas and connections to include. The decision-making process may foster the generation of criteria to distinguish pivotal ideas. Clustering related ideas in spatial proximity can support learners' reflections on shared properties of and relationships between ideas. Links between ideas from different areas can be seen as indication for knowledge integration across different contexts. Concept maps may support making sense of ideas by eliciting semantic relationships between ideas (see table 1). Concept maps can change students' understanding beyond remembering isolated ideas to constructing meaningful connections of organized knowledge (Bransford, Brown, & Crocking, 2000). Mason (1992) observed that students exposed to 'mapping' during instruction demonstrated "insight into the interrelatedness of concepts" (p. 60), instead of seeing scientific knowledge as a collection of isolated facts.

Knowledge integration suggests that a successful curriculum starts by eliciting existing alternative ideas about scientific phenomena. Learners need tools to elicit their existing ideas and distinguish alternative ideas. Ideas cannot be understood in isolation but need to be connected to existing ideas (Bruner, 1960). Learning an idea means seeing it in relation to other ideas, distinguishing it from other ideas, and being able to apply it in specific contexts. To learn a subject is to have actively integrated key ideas and the relations between them.

Knowledge integration activities are designed to help learners construct more coherent understanding by developing criteria for the ideas that they encounter. Research suggests that concept mapping is especially efficient, in comparison to other interventions such as outlining or defining ideas, for learning about the relations between ideas (Cañas et al., 2003). Concept maps as knowledge integration tools elicit ideas as nodes (concepts) and relations between ideas as labeled arrows. The visual format of concept maps can foster critical distinctions between alternative ideas and relationships, either individually or through collaboration in communities of learners.

Cognitive science research (for example see Bransford, Brown, & Crocking, 2000) indicates that new ideas need to be connected to existing ideas to be stored in the long-term memory. Eliciting existing ideas brings them from long-term memory to working memory. Learners make sense of new ideas by integrating them into their existing repertoire of ideas.

Knowledge integration suggests that ideas should be presented in multiple contexts and support generation of connecting ideas across contexts. Multiple representations of ideas (for example dynamic visualizations, animations, pictures, or diagrams) can facilitate learning and performance supporting different accounts of scientific phenomena (Pallant & Tinker, 2004; Ainsworth, 2006), for example by complementing each other or constraining interpretations (Ainsworth, 1999). However, learners making connections between different representations can be challenging as the representations are connected through multiple relations that are often not intuitively obvious to the learner (Duncan & Reiser, 2005).

Table 1
Concept mapping for knowledge integration

Knowledge Integration Process	**Concept Mapping Activity**
Eliciting existing ideas	Concept maps can be used as a pretest activity to elicit' existing concepts.
Adding new ideas and connecting to existing ideas in learners' repertoires	New concepts can be added to existing propositions in a concept map. If several alternative relations between two concepts are possible, learners have to decide which one to use in the map. If applicable, learners decide which concepts to add to the map.
Distinguishing/ Critiquing ideas	After adding new concepts, concepts can be rearranged into new groups, and the concept map network structure might need revision to reflect the new concepts.
Sorting out ideas/ Refining	Different sources of evidence can be used as references to sort out concepts and further refine the concept map.
Applying ideas	Concept maps can be used as resources to generate explanations of scientific phenomena.

3. Concept maps as versatile tools

Initially, concept maps were used by researchers to elicit relations between alternative science ideas from clinical student interviews (Novak & Gowin, 1984; Novak & Cañas, 2006). Since the first conception of Novakian concept maps, concept maps have been

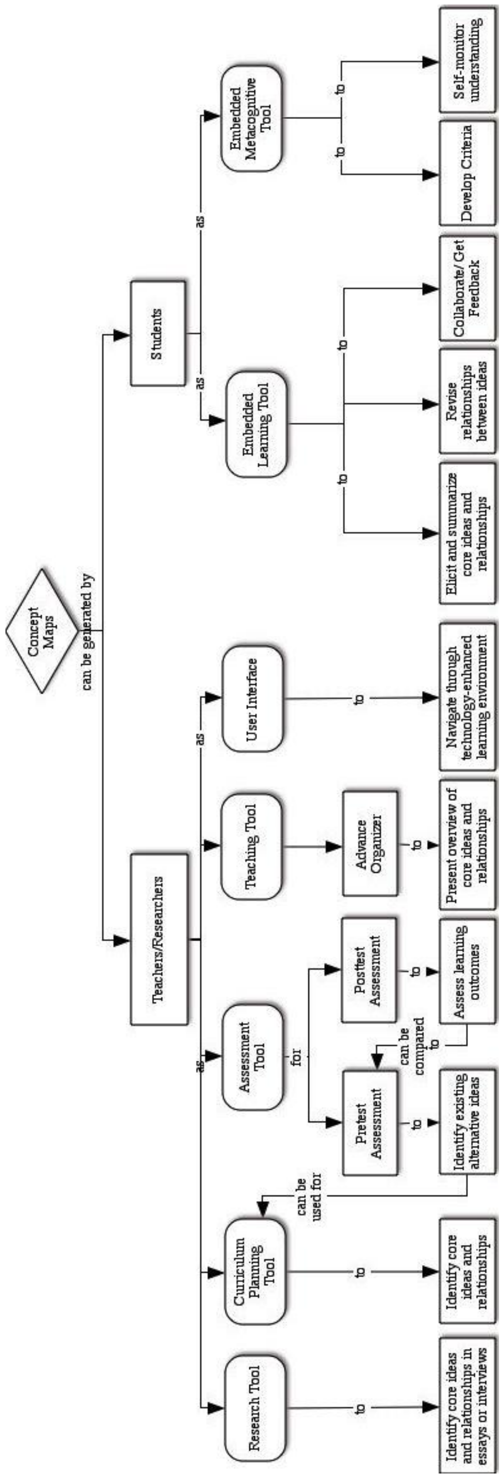

Fig. 1. Different uses of concept maps

implemented with a wide variety of users in a wide variety of settings (Cañas et al., 2003). Daley and Torre concluded that concept maps are used mainly in four different ways: 1) by promoting meaningful learning; 2) by providing an additional resource for learning; 3) by enabling instructors to provide feedback to students, and 4) by conducting assessment of learning and performance (Daley & Torre, 2010). This paper distinguishes between concept maps generated by curriculum designers (teachers or researchers) and learners (see Fig. 1). For review purposes, this paper structures concept mapping studies according to their focus on learning, metacognition, collaboration, and assessment. In practice, concept mapping activities often combine several of these features, for example by supporting collaborative learning activities that require self-monitoring and critique (metacognition) (for example see Schwendimann, 2014b).

As illustrated in Fig. 1, concept maps can be generated by curriculum designers (teachers or researchers) or students. Curriculum designers can use concept maps to identify core ideas and knowledge structures when designing or revising curricula (for example Starr & Krajcik, 1990; Martin, 1994; Edmondson, 1995). Concept maps can be used as assessment tools, for example concept maps can serve as pretests or as embedded formative assessments to identify students' prior ideas, which can be used to design curricula that connect to existing alternative ideas and provide feedback. Concept maps can be used as summative assessments to track changes in students' understanding (see Concept Maps as Assessment Tools). Concept maps can be used as advance organizers to provide an overview of core ideas prior to instruction (for example see Mistades, 2009) and illustrate the (otherwise often hidden) structures of knowledge. In technology-enhanced learning environments, concept maps can serve as dynamic user interfaces to navigate through activities (for example see Puntambekar, Stylianou, & Huebscher, 2003).

As learning tools, students can generate concept maps to elicit, summarize, and revisit core ideas and relations (Kinchin, 2000a) (see Concept maps as Learning Tools). Concept maps can serve as shared artefacts to support collaborative learning (Gaines & Shaw, 1995; Cicognani, 2000; Cañas, Suri, Sanchez, Gallo, & Brenes, 2003), for example in decision making, or giving and receiving feedback from teachers and peers (see Concept Maps as Collaborative Tools). Generating concept maps can promote students' self-monitoring of their understanding and scaffold building criteria to distinguish and sort out alternative ideas (see Concept Maps as Metacognitive Tools).

The following sections of the paper discuss concept maps as learning, metacognitive, assessment, and collaborative tools in more detail.

3.1. Concept maps as learning tools

Complex fields of knowledge, such as different areas of science, consist of a large number of ideas that are connected in different ways. In the context of biology, Schmid and Telaro commented that: "The schools' favored approach to teaching unfamiliar material is rote learning. Rote learning predictably fails in the face of multilevel, complex interactions involved in biology. Concept mapping ... stresses meaningful learning, and appears to be ideally suited to address biological content" (Schmid & Telaro, 1990, p. 78-79). As a learning tool, concept maps can support knowledge integration processes by eliciting core ideas and connections, and making possible clusters or hierarchies visible. Watson (2005) found that graphic organizers such as concept maps can scaffold integrating students' isolated ideas towards an organized interconnected network of ideas. Research indicates that the implementation of concepts maps can shift the epistemological authority from the teacher to the student, reduce emphasis on right and wrong answers, and create visual entry points for learners of varying abilities (Roth & Roychoudhury, 1993a; O'Donnell, Dansereau, & Hall, 2002).

Several meta-analyses reviewed the effects of concept maps as learning tools. Horton et al. (1993) compared the effects of concept mapping reported in 19 classroom-implemented quantitative studies. The meta-analysis found that concept maps as learning tools produced generally medium-sized positive effects on student's achievement and large positive effects on student's attitudes. The mean effect size for studies using pre-made maps was 0.59. Concept maps generated by students in groups produced a mean effect size of 0.88. Nesbit and Adesope (2006) conducted a meta-analysis of fifty-five experimental and quasi-experimental studies in which students learned how to use concept maps. The study included 5,818 students ranging from fourth grade to postsecondary in fields such as science, psychology, statistics, and nursing. Across different conditions and settings, the study found that the use of concept maps was associated with increased knowledge retention, with mean effect sizes varying from small to large depending on how the concept maps were used. Cañas et al. (2003) found concept maps to be effective learning tools with generally positive effects on knowledge acquisition. Kinchin critically reviewed recent studies on concept maps as learning tools in higher education and pointed out that review studies need to distinguish different forms of concept map activities (Kinchin, 2014). The effectiveness of concept maps as learning tools depends to some degree on finding the right degree of freedom to match the task and the abilities of learners. Concept maps range from very constrained forms (fill the blanks) to no constrictions (blank worksheet) (Cañas, Novak, & Reiska, 2012).

In science education, concept maps have been investigated as learning tools in a wide variety of different fields from K-12 to higher education (see table 2). Concept mapping research has mainly focused on science classrooms but has been extended to include a wide variety of disciplines and contexts, for example language, mathematics, and history education (Kinchin & Hay, 2007). Study participants have ranged from elementary to higher education students, for example middle school students (Coleman, 1998; Sizmur & Osborne, 1997), high school students (Stensvold & Wilson, 1990), university students (Heinze-Fry & Novak, 1990; Pearsall, Skipper, & Mintzes, 1997; Kinchin, 2014), and pre-service teacher students (Mason, 1992). Concept maps can represent very simple partial ideas to complex connected networks of ideas, which make them usable for a wide range of learners. For example, Kern and Crippen (2008) used embedded concept maps in a one-month long biology unit. Using the electronic concept mapping tool Cmap (Cañas, 2004), students individually generated concept maps from a given list of ideas and revised them three more times throughout the curriculum. Students received feedback from peers and the teacher. Findings indicate that embedded concept maps can support students' integration of biology ideas and reveal conceptual changes in students' understanding. To track conceptual changes of students' ideas in a university course, Trowbridge and Wandersee (1994) asked college students to individually generate concept maps to summarize specific lectures. Students generated ten different concept maps from a given list and self-chosen ideas. The instructor graded all concept maps and provided feedback. Results suggest that changes in superordinate core ideas can indicate conceptual changes in students' understanding of complex ideas.

Table 2
List of studies of concept maps as science learning tools by subject

Subject	References
Chemistry	Stensvold & Wilson, 1990; Markow & Lonning, 1998; Brandt et al., 2001; Nicoll, Francisco, & Nakhleh, 2001; Liu, 2004; Uzuntiryaki & Geban, 2005; DeMeo, 2007; Oezmen, Demircioglu, & Coll, 2009; BouJaoude & Attieh, 2008; Kaya, 2008; Aydin, Aydemir, Boz, Cetin-Dindar, & Bektas, 2009; Mun, Kim, Kim, & Krajcik, 2014
Physics	Bascones, Venezuela, & Novak, 1985; Moreira, 1987; Pankratius, 1990; Carey & Spelke, 1994; Roth, 1994; Roth & Roychoudhury, 1994; Adamczyk & Willson, 1996; Pushkin, 1999; Reiska, Dahncke, & Behrendt, 1999; Anderson, Lucas, & Ginns, 2000; Van Zele, Lenaerts, & Wieme, 2004; Mistades, 2009
Earth Science	Ault, 1985; Hoz, Tomer, Bowman, & Chayoth, 1987; Rebich & Gautier, 2005; Snead & Snead, 2004; Englebrecht, Mintzes, Brown, & Kelso, 2005; Hsu, Wu, & Hwang, 2008; Hsu, 2008
Biology	Stewart, 1979; Novak, 1980; Heinze-Fry & Novak, 1990; Schmid & Telaro, 1990; Wallace & Mintzes, 1990; Okebukola, 1992; Trowbridge & Wandersee, 1996; Wandersee, Wissing, & Lange, 1996; Pearsall, Skipper, & Mintzes, 1997; Fisher, Wandersee, & Moody, 2000; Kinchin, 2000a; Cakir & Crawford, 2001; Chang, Sung, & Chen, 2001; Kinchin, 2001; Mintzes, Wandersee, & Novak, 2001; Odom & Kelly, 2001; Tsai & Huang, 2002; Brown, 2003; Preszler, 2004; Kinchin, De-Leij, & Hay, 2005; Buntting, Coll, & Campell, 2006; Keraro, Wachanga, & Orora, 2007; Chang, 2007; Hmelo-Silver, Marathe, & Liu, 2007; Mintzes & Quinn, 2007; Kern & Crippen, 2008; Byrne & Grace, 2010; Cathcart, Stieff, Marbach-Ad, Smith, & Frauwirth, 2010
Ecology	Brody, 1993; Heinze-Fry, 1998
Astronomy	Zeilik et al., 1997
Medicine	Mahler, Hoz, Fischl, Tov-Ly, & Lernau, 1991; Edmondson, 1993; Edmondson, 1995; Irvine, 1995

Research indicates that concept mapping as learning tools may be particularly beneficial for lower performing students (Stice & Alvarez, 1987; Spaulding, 1989; O'Donnell, Dansereau, & Hall, 2002; Snead & Snead, 2004; Wise, 2009) and students with learning disabilities (Crank & Bulgren, 1993). Concept map activities can help low performing students to a greater degree because they model the active inquiring approach often found in higher performing students (Cañas et al., 2003), and it can provide scaffolds for a more organized and deliberative approach to learning. The minimal number of words and propositional forms used to represent ideas in a concept map might be beneficial especially for English language learners (ELL) and students of low academic abilities (Schmid & Telaro, 1990).

3.2. Concept maps as metacognitive tools

Concept maps can also be used as metacognitive tools that support learners by eliciting existing connections and reveal missing connections between ideas, especially cross-connections (Shavelson, Ruiz-Primo, & Wiley, 2005). This can help students to reflect and contrast their existing ideas with new ideas in the learning material. It can encourage students to build on their own ideas, rather than isolate new ideas from existing knowledge. Several WISE studies found that monitoring your own learning progress through reflection encourages students to revisit and reorganize their ideas (Chiu, 2008; Chiu, 2009).

Eliciting one's understanding can promote student self-monitoring of their learning progress and support generating self-explanations. Self-explanations as an attempt to make sense of new ideas have been found beneficial for the integration of ideas (Chi, 2000). Ritchhart, Turner, and Hadar (2009) found that concept maps as a metacognitive tool can support student self-reflection about their conceptions of thinking and thinking processes. The reflection on links in concept maps can contribute to the development of reasoning skills (McMillan, 2010). Especially in less constrained concept map tasks, learners need to make decisions about which ideas and/or links to include in their map. Concept maps do not aim to include every possible idea and connection but a careful selection. Students need to generate criteria to identify and distinguish core ideas and their connections from alternative ideas and connections. Concept map generation and revision activities can encourage learners to revisit, reflect on, and revise their existing ideas. Critiquing is the process of creating a set of criteria, applying criteria to compare one's own or other's alternative ideas against each other, reflecting on how those ideas apply to alternative ideas, and selecting supported ideas based on evidence (Shen & Confrey, 2010). Critique activities require students to use or develop criteria to reflect, revise their work, and self-monitor their learning progress (Chi, 2000) that can foster the development of metacognitive skills for lifelong autonomous learning. Critique activities encourage the elaboration of ideas and conjectures. Asking students to critique has been found to facilitate the development of coherent and generative criteria (Slotta & Linn, 2000).

Critique is often applied in collaborative settings. In science, peer critique is a central aspect of the nature of science (Ford, 2008). Scientific knowledge is collaboratively constructed by the scientific community, which evaluates each other's theories and findings (Wenger, 1998). Learners' views of the nature of science influence their willingness to critique (Schwarz & White, 2005; Tabak, Weinstock, & Zvilling-Beiser, 2009). Many students seem to hold the objectivist view that scientific knowledge is discovered and static (Marcum, 2008) rather than consisting of constructed tentative models. When scientific ideas are understood as immutable products there is little reason to critique. Linn and Eylon (2006) noted that critique activities can engage students to "question scientific claims and explore the epistemological underpinnings of scientific knowledge" (p. 536).

From a situated learning perspective, critique activities in the classroom can mimic what professionals do in their communities (Lave & Wenger, 1991). Critiquing peer work can provide a driving force for revising one's own work (Lehrer & Schauble, 2004). The social process of reaching agreement is critical in shaping one's ideas (Clark & Sampson, 2008; Enyedy, 2005).

In science education, collaboratively critiquing ideas requires learners to argue, negotiate, and make informed decisions (Berland & Reiser, 2009). Finding common ground can be a driving force for critique. To reach such common ground, students need to pose questions, make revisions, accept propositions, defend against criticism, and improve their criteria (Shen & Confrey, 2007). Brown and Campione (1996) showed that elementary students can form communities of learners that constructively share resources and review each other's work. Students need authentic opportunities to develop criteria to distinguish valid alternative ideas based on evidence and scrutinize the reliability of sources (Cuthbert & Slotta, 2004; Davis & Kirkpatrick, 2002). DiSessa (2002; 2004) found that students are able to develop their own criteria to critique representations. A meta-study by Falchikov and Goldfinch (2000) found that student-generated criteria work better for peer assessment than using a set of given criteria.

However, students have usually little opportunity to critique (Grosslight, Unger, Jay, & Smith, 1991; Clark, 2000; Shen & Confrey, 2010). Students can a) critique their own ideas, b) a peer's ideas, c) common alternative ideas, or d) experts' ideas.

a) Critiquing one's own ideas: Research indicates the difficulty of critiquing one's own work, for both experts and novices (Guindon, 1990). People tend to discount ideas that contradict their existing ideas (Kuhn, 1962; Schauble, Glaser, Duschl, Schulze, & John, 1995; Chinn & Brewer, 2001). For example, students as well as professional engineers often stick to their initial design strategies and resist alternative ideas (Cuthbert & Slotta, 2004).

b) Critiquing a peer's ideas: Analyzing a peer's work may be easier than evaluating expert generated work. Critiquing peer work can motivate students to improve their own work and better understand what needs to be revised. Comparing one's own ideas against those of a peer, can help students to value their own ideas while developing criteria to critically review them. However, critiquing peers can be socially difficult as students tend to give overly generous or overly critical feedback (Hoadley & Kirby, 2004). Schwendimann found that critiquing peer-generated concept maps anonymously can facilitate productive feedback and improve the quality of concept maps in subsequent revision steps (Schwendimann, 2014b).

c) Critiquing common alternative ideas: Providing students common alternative ideas can serve as a starting point for critique. Critiquing and revising concept maps with deliberate flaws are partial solutions that require a completion strategy (Van Merriënboer, 1990; Sweller, Van Merrienboer, & Paas, 1998; Chang, Chiao, Chen, & Hsiao, 2000). Giving all students the same artifact equalizes conditions, compared to a peer-critique activity where each student receives different ideas from peers. On the negative side, having to compare, critique, and select ideas from three different sources (for example two collaborating group members and a given concept map) could increase cognitive load in some students.

d) Comparing one's own ideas to expert ideas could help students identify gaps in their understanding. Previous studies using expert-made concept maps often presented maps to students as a form of summary to be studied (O'Donnell, Dansereau, & Hall, 2002). In these settings, students did not actively generate their own connections or critically evaluate presented propositions. A meta-analysis (Horton et al., 1993) found that studying expert-made and student-generated concept maps seemed to have an equally positive effect on improving students' achievement. On the other hand, Cliburn (1990) noted that teacher-generated concept maps could support integrative understanding. O'Donnell, Dansereau, and Hall (2002) found that students could recall more central ideas when they learned from expert-made knowledge maps than when they learned from texts. Students with low verbal ability or low prior knowledge often benefited the most. Chang, Sung, and Chen (2001) compared generating concept maps to critiquing them using a computer-based tool that provided feedback by comparing student-generated maps to an expert-generated benchmark map. Generating and critiquing concept maps led to similar results, both better than a control group that did not use concept maps. However, Novak (1980) observed that studying pre-made expert maps in genetics instruction could be confusing to some students as expert-generated concept maps could be seen by students as the one correct solution. According the underlying constructivist view of concept maps, expert-generated maps can be useful but should not be presented as final answers but as one of many possible solutions.

3.3. Concept maps as collaborative tools

Concept maps can not only be seen as cognitive tools that help eliciting ideas and metacognitive tools that help supporting the generation of self-explanations, but also as social artifacts through which students communicate (Roth & Roychoudhury, 1993b). The spatial arrangement of concept maps allows for fast information retrieval (Hook & Boerner, 2005), which can support social interaction. The high degree of explicitness makes concept maps an exceptional vehicle for exchanging ideas during collaborative knowledge construction. Several studies have reported that students who collaboratively generated concept maps achieved higher scores than those who constructed their concept maps individually (Okebukola & Jegede, 1989; Okebukola, 1992).

A social approach to concept mapping emphasizes the communicative function of this inscription. Inscriptions are different forms of external representations, and are central to the construction of knowledge in scientific practice (Roth & McGinn, 1998; Lehrer, Schauble, Carpenter, & Penner, 2000). From a cognitive apprenticeship perspective (Collins, Brown, & Holum, 1991), it is therefore valuable for students to gain expertise through constructing and interpreting inscriptions used in scientific practice. When concept maps are generated collaboratively in dyads or groups, they become shared social artifacts that elicit existing and missing connections and spur discussion among students and teachers. Both concept maps and collaborative learning have been found to have educational benefits (Cañas et al., 2003). Combining the two could produce synergistic beneficial effects. As each proposition can consist of only one link, students are required to negotiate which connection to revise or newly generate. Berland and Reiser (2009) found that trying to persuade a peer of your ideas encourages students to support their ideas with scientific evidence.

Having to make a decision about which connection to revise or add creates an authentic need for effective criteria and supporting evidence to distinguish among ideas in students' repertoires (see Concept maps as metacognitive tools). Students need to determine which ideas are more effective, valuable, or more scientifically normative than others. This negotiation process is expected to encourage students to use evidence found in the curriculum to support their decision-making. This activity asks students to learn from each other and reach a shared consensus rather than just being responsible for obtaining the "right" answer from the teacher. This activity requires students to revisit their existing ideas and compare and contrast them to the new ideas introduced in the curriculum. The concept map becomes a social support for prompting students to articulate their understanding and integrate their knowledge through reflection.

3.4. Concept maps as assessment tools

Many conventional forms of assessment, such as multiple-choice, true/false, and fill-the-blanks, focus on recall of isolated ideas (Ruiz-Primo, Iverson, & Yin, 2009). Hyerle

(1996) has called for a shift in the focus of future teaching, learning, and assessment away from rote recall of "isolated things" towards recognition of "how students interactively construct the pattern that connects" (p. 20). Concept maps can be used as assessment tools to elicit students' connections between ideas (Edmondson, 2000; Ruiz-Primo, 2000; Stoddart, Abrams, Gasper, & Canaday, 2000; Mintzes, Wandersee, & Novak, 2001; Hay, 2008; Popova-Gonci & Lamb, 2012) and track changes in students' understanding of relations between ideas (Ruiz-Primo & Shavelson, 1996). Quantitative or qualitative concept map indicators can track changes in students' knowledge integration of complex ideas (Schwendimann, 2014a). Concept map assessments have been found to show varying correlations with conventional tests - depending on the type of conventional test, the concept map activity design, and the concept map scoring system (Stoddart, Abrams, Gasper, & Canaday, 2000). More constrained forms of concept map assessment have been found to be highly correlated with multiple-choice tests (Liu & Hinchey, 1993; Liu & Hinchey, 1996; Schau, Mattern, Weber, Minnick, & Witt, 1997; Rice, Ryan, & Samson, 1998). Course grades in a university biology course showed moderate correlation to concept mapping scores (Farrokh & Krause, 1996). Osmundson reported a moderate correlation between middle school essays and concept maps (Osmundson, Chung, Herl, & Klein, 1999). Since 2009, concept maps have been used in standardized large-scale assessments in the U.S. National Assessment of Educational Progress (NAEP) to measure changes in conceptual understanding of science ideas (Ruiz-Primo, Iverson, & Yin, 2009).

Concept maps as assessment tools have been used to assess prior ideas and/or changes in conceptual understanding in a wide variety of contexts (Ruiz-Primo & Shavelson, 1996; Edmondson, 2000; Mintzes, Wandersee, & Novak, 2001; Ruiz-Primo, 2000). Table 3 shows a selection of concept map activities implemented with different age groups in different science class settings. (The studies shown in table 3 serve to illustrate the range of concept map implementations and do not aim to represent a comprehensive review. Google scholar lists over 56'000 publications on concept mapping and science alone (Oct 2014).

Table 3
A selection of research on concept maps as assessment tools (in science education)

School Level	**Science**	**References**
Kindergarten	General Science	Stice & Alvarez, 1987; Mancinelli, Gentili, Priori, & Valitutti, 2004; Birbili, 2006
Elementary School	General Science	González, 1997
Middle School	General Science	Rice et al., 1998; Osmundson et al., 1999; Guastello, Beasley, & Sinatra, 2000; Snead & Snead, 2004; Gerstner & Bogner, 2009
High School	Biology	Novak, Gowin, & Johansen, 1983; Demastes et al., 1995; Kinchin, 2000a; Banet & Ayuso, 2003; Royer & Royer, 2004; Chang, 2007; Wise, 2009
	Physics	Rye & Rubba, 2002; Yin, Vanides, Ruiz-Primo, Ayala, & Shavelson, 2005
	Earth Science	Hsu et al., 2008

	Chemistry	Ruiz-Primo, Schultz, Li, & Shavelson, 2001; Liu, 2004; Uzuntiryaki & Geban, 2005
Undergraduate	Biology	Pearsall et al., 1997; Buntting et al., 2006; Cathcart et al., 2010;
	Chemistry	Nicoll, 2001
	Computer Science	Acton, Johnson, & Goldsmith, 1994
	Earth Science	Rebich & Gautier, 2005
	Physics	Mistades, 2009
	Mathematics/ Statistics	Schau & Mattern, 1997
Graduate/ Post-Graduate	Medical/ Nursing school	Irvine 1995; Van Neste-Kenny, Cragg, & Foulds, 1998; West, Pomeroy, Park, Gerstenberger, & Sandoval, 2000; Bruechner & Schanze, 2004; Vilela, Austrilino, & Costa, 2004; Veo, 2010; Chen, Liang, Lee, & Liao, 2011; Maneval, Filburn, Deringer, & Lum, 2011; Nejat, Kouhestani, & Rezaei, 2011; Sarhangi et al., 2011; Schuster, 2011; Taylor & Littleton-Kearney, 2011; Tseng et al., 2011; Nijman, Sixma, Triest, Keus, & Hendriks, 2012; Atay & Karabacak, 2012; Gerdeman, Lux, & Jacko, 2013
	Biomedical Engineering	Walker & King, 2002
	Research Methods	Hay, 2007
	Vocational education (VET)	Koopman, Den Brok, Beijaard, & Teune, 2011; Koopman, Teune, & Beijaard, 2011; Schaap, Van der Schaaf, & De Bruijn, 2011; Van Bommel, Kwakman, & Boshuizen, 2012
Science Teachers	Science	Rutledge & Mitchell, 2002; Nehm & Schonfeld, 2007; Koponen & Pehkonen, 2010; Koc, 2012

Concept mapping can offer several advantages over conventional assessment forms. 1) Unlike recall oriented assessment forms, concept maps are generative forms of assessment that can also reveal partial understanding. 2) To understand and use ideas, ideas need to be connected to existing ideas. Interconnection between ideas is an essential property of knowledge. One aspect of competence in a field is well-integrated and structured knowledge (for example see Novak & Gowin, 1984; Chi, Glaser, & Farr, 1985; Bransford, Brown, & Crocking, 2000). Cognitive psychologists postulated that "the essence of knowledge is structure" (Anderson, 1984, p. 5). Unlike traditional forms of assessment that focus on recall of isolated ideas (isolated nodes in a concept map), concept maps represent connections between ideas (links between nodes). 3) Experts and successful students develop well-differentiated and highly integrated frameworks of related ideas (Chi, Feltovich, & Glaser, 1981; Mintzes, Wandersee, & Novak, 1997; Pearsall, Skipper, & Mintzes, 1997). Concept maps can reveal students' knowledge organization by showing connections, clusters of ideas, hierarchical levels, and cross-links between ideas from different levels (Shavelson, Ruiz-Primo, & Wiley, 2005). Cross-links are of special interest as they can indicate creative leaps on the part of the knowledge producer (Novak & Cañas, 2006). 4) The form of assessment directs students learning. Concept mapping can foster students' learning for conceptual understanding instead for memorization of isolated ideas (see Concept Maps as Learning Tools). 5) Research indicates that concept maps can assess different kinds of knowledge than conventional assessment forms (Ruiz-Primo, 2000; Shavelson, Ruiz-Primo, & Wiley, 2005; Yin et al., 2005).

4. Discussion and implications

Students and instructors in higher education require powerful tools to make sense of the ever-increasing complexity of ideas. To answer the question in which age group concept maps can be implemented, the rich literature on concept mapping suggests that concept maps can be implemented in a wide variety of settings, from Kindergarten to university level. What can concept maps be used for? Concept maps have been used as formative and summative assessment tools, as learning tools, as advance organizers, as user interfaces, as metacognitive self-monitoring tools, and as collaboration tools. Regarding the subjects in which concept maps can be implemented, concept maps have been successfully implemented in all STEM subjects (including chemistry, physics, earth science, biology, ecology, astronomy, computer science, engineering, mathematics, and medicine) as well as language education, history education, pre-service teacher education, and vocational education.

However, concept mapping activities are often implemented in piecemeal fashion instead of systematic usage across subjects and school levels. This makes it difficult for learners to develop proficiency in concept mapping and make concept mapping a personal tool to support their lifelong learning processes. Kinchin (2000b) suggested that concept maps as learning tools should be introduced early in students' educational careers, ideally before preferred study habits have been firmly established (Gallenstein, 2005). When introducing concept maps, the teacher outline the potential benefits for learners, for example to reflect, to communicate what would otherwise be incommunicable, or to keep trace of what otherwise would disappear (Lehrer, Schauble, Carpenter, & Penner, 2000). Students need frequent opportunities to practice the whole cycle of concept mapping, from generating concept maps to reviewing and revising concept maps. Reviewing concept maps can be a collaborative process that contributes to self-monitoring (Schwendimann, 2014b). By engaging students in knowledge integration processes, they can learn to self-monitor their learning progress and take an active role in refining their knowledge. Mintzes et al. described concept maps as "the most important meta-cognitive tool in science education today" (Mintzes, Wandersee, & Novak, 1997, p. 424). Developing self-monitoring skills for their own understanding can help students to become lifelong learners.

A complete concept map activity should consist of a) a concept map training phase, b) a concept map generation task, c) and a concept map revision activity (Schwendimann, 2011). Concept map training activities are not only essential for students but also for instructors. Concept maps should be introduced in pre-service teacher education and pedagogical courses for instructors in higher education. Instructors might be more likely to implement concept maps in their classes when they feel confident generating and evaluating concept maps themselves. Understanding concept mapping might require changing one's conceptions of learning and teaching. Concept maps are aligned with the constructivist view that learners need to construct their own knowledge by building on their existing knowledge. Teacher and learners who focus on rote memorization of isolated ideas might struggle to see the advantages of concept maps as learning tools (Kinchin, 2001). An introduction to concept mapping for instructors should include first-hand experiences, a discussion of the learning theories underlying concept mapping, and an overview of different forms of concept mapping activities. The success of a concept map activity depends greatly on the kind of concept map chosen and the skillfulness of the implementation (Cañas, Novak, & Reiska, 2012). Instructors need to make informed decisions which form of concept map suits which task and learner. Concept maps can be implemented in different social settings, from individual usage to small groups and whole class discussions. The visual features of concept maps supports their use as shared artifacts for collaborative activities, such as scaffolded generation and critique activities.

When used sensibly and skillfully, concept maps can be powerful tools to support knowledge integration processes of complex ideas. However, concept maps should not be seen as isolated tools but as complementary instruments to be used in concert with other learning and assessment tools. To prepare students how to make sense of complex ideas, instructors and students should have many different tools at their disposal and learn when to make use of which particular tool. Concept maps should be available in every learner's 'toolbox', from Kindergarten to higher education, as powerful and versatile tools that can support knowledge integration of complex ideas in school and throughout lifelong learning.

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