Online concept maps in medical education: Are we there yet?

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Abstract

Background: Concept maps are widely used in education to promote meaningful learning, critical thinking and problem-solving skills. Such maps are of particular interest within medical education because concept mapping is a form of active learning, which can foster the life-long learning medical students require to manage an ever-increasing body of knowledge.

Issues: Despite these benefits, the introduction of concept maps in curricula can often be met with resistance. To overcome this obstacle, providing varying levels of guidance, i.e., scaffolded versus self-constructed concept maps, may be more suited to novice and experienced students, respectively. Furthermore, immediate feedback (known to enhance student learning and motivation) is difficult and time-consuming to provide.

Conclusions: As such, future research into concept mapping would benefit from the development and validation of automated tools for their assessment. Although concept maps are effectively utilised within limited contexts in medical education, consideration of how they can be most effectively employed is needed.

Keywords: medical education; medical students; computer-assisted instruction; review.

Background

What are concept maps?

Concept maps are graphical tools used for organising and representing knowledge, developed by Novak and Gowin in the 1970s (Novak, 1990). They are comprised of concepts (regularities in events or objects enclosed in circles or boxes) that are linked to one another with lines or arrows. They are most commonly created with the use of

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computer software such as CmapTools™. Linking phrases are included with the lines to describe the relationship between concepts. A concept-link-concept set is called a proposition (a meaningful statement about an object or event). Concept maps are characteristically hierarchical, with broader terms placed at the top. Another important feature of concept mapping is the use of cross-links, showing the relationships between concepts from different domains. Examples can be included to help clarify the meaning of a specific concept (Canas et al., 2003).

Theoretical basis of concept maps

The fundamental aim of concept mapping is to promote meaningful learning (Novak, 1990). Novak and Gowin developed concept mapping in accordance with Ausubel's theory of assimilation, the central idea of which is that learning occurs when new information is integrated into an existing concept and propositional framework; therefore, "the most important single factor influencing learning is what the learner already knows" (Ausubel, 1968, p. vi). Meaningful learning (the integration of new knowledge with existing understanding) is hence distinguished from rote learning (memorisation of concept definitions and statements). Importantly, meaningful learning using concept maps shifts the responsibility for learning away from the instructor onto the student (Watson, 1989). Although vast amounts of information can be retained in long-term memory via rote learning, with little integration, this is both easily forgotten and more difficult to apply in different circumstances (Novak & Canas, 2008; Rendas, Fonesca, & Pinto, 2006).

Benefits of learning with concept maps

Over recent decades, the use of concept maps for learning has been on the rise, with a growing body of research showing mostly positive results. In particular, meaningful learning, critical thinking and problem solving have been demonstrated as benefits of using of concept maps (Daley & Torre, 2010).

Concept mapping can enhance the development of critical thinking and problem-solving skills (Daley, Shaw, Balistrieri, Glasenapp, & Piacentine, 1999). Even when students are merely provided with an expert map rather than being asked to construct their own, concept maps can aid learning by enhancing the understanding of relationships and providing multiple retrieval paths (O'Donnell, Dansereau, & Hall, 2002). Gonzalez, Palencia, Umana, Galindo and Villafrade (2008) demonstrated that while there was no difference in multiple-choice question (MCQ) performance, groups given a concept mapping task performed better in later problem-solving questions (which require recall, transfer and application of knowledge) than those receiving the traditional teaching method of group discussion. This difference was particularly marked for students with the lowest baseline competence.

A common problem that educators face is encouraging students to learn not simply for the sake of assessment. In fact, assessment drove learning even amongst a sample of postgraduate nursing students, who simply used discussion groups as a means to gain the information they needed in order to pass (Willis et al., 2002). Students overlooked

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benefits such as developing the ability to think creatively, learning to integrate knowledge from a range of fields and identifying gaps in their understanding. While one approach could be to educate students about the benefits beyond assessment-driven learning, we could also change our assessment methods to reflect the knowledge and skills that we wish our students to develop. Traditional assessment methods concentrate on measuring knowledge that students have mastered over a course of study and not how well-integrated those distinct pieces of knowledge are. This reduces motivation for students to learn in a way that emphasises integrated meaningful learning, since benefits can be hard to observe directly, and there is little understanding of how this could improve their academic results (Edmondson, 2005). By assessing meaningful learning, concept map assessments might foster an environment in which the goal of learning is not academic performance, but increasing knowledge and understanding (Edmondson & Smith, 1998).

Use of online concept maps in medicine to promote learning

Within health professional education, and medical education in particular, there has been a shift from the almost ubiquitous use of didactic lectures towards methods of teaching that involve active learning, requiring more engagement from the student (Surapaneni & Tekian, 2013). This is especially the case due to the constantly growing body of knowledge in medicine, which demands meaningful, lifelong learning for medical students and practitioners (Daley et al., 2006). Active learning and collaboration by medical students foreshadow the skills that will be required to work in a multidisciplinary team for patient-centred medicine (Kanthan & Mills, 2005).

A randomised controlled trial by Surapaneni and Tekian (2013) showed that a group of students who used concept maps achieved superior academic performance in biochemistry, despite receiving the same amount of teaching on the subject from the same member of faculty. The concept maps helped to develop students' reasoning and clinical collaborative skills. Since concept maps are created and stored electronically, as learning continues throughout and beyond medical school, those maps that were previously made by students could even be adapted and elaborated upon as students gain new knowledge. Concept maps may support the development of physicians who are able to make clinical decisions based on thorough understanding and are committed to being lifelong, self-directed, meaningful learners (Pintoi & Zeitz, 1997).

Concept mapping can help bridge the gap between theory and practice. The process of constructing maps parallels clinical practice wherein students must justify the links between different concepts and ideas. This encourages the formation of hypotheses, leading students to approach the problem from different perspectives (Mok, Whitehill, & Dodd, 2008). Furthermore, pattern recognition skills learnt through the mapping process can enhance students' ability to formulate differential diagnoses (Torre et al., 2007). Indeed, the creation of concept maps by groups using a set of given terms with facilitated discussion improved medical students' ability to answer diagnostic and pathophysiological questions (Saeidifard, Heidari, Foroughi, & Soltani, 2014). A study of graduate nurses found that concept maps accelerated nurses' ability to synthesise

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and prioritise information, formulate care plans and make appropriate decisions in clinical scenarios (Wilgis & McConnell, 2008). Concept maps enable an overview of the entire clinical picture, thereby promoting a comprehensive understanding of a case (All, Huycke, & Fisher, 2003).

Even in programs reliant upon problem-based learning (intended to facilitate integrated learning), many students find it difficult to integrate new information with existing knowledge when applying basic sciences to clinical scenarios and transferring information from one context to another (such as from a practical class to a tutorial). Concept maps have been shown to help students integrate their understanding of physiological mechanisms, as well as challenge their grasp of the subject matter by helping to identify gaps in knowledge. Much of this seems to relate to the capacity of concept maps to demonstrate a learner's level of understanding to teachers, which would otherwise be difficult to perceive (Veronese, Richards, Pernar, Sullivan, & Schwartzstein, 2013).

One discipline within medicine where concept mapping might be particularly helpful is pathology. This is because the study of pathology requires the integration of concepts and ideas (i.e., of physiological functions, effects and processes of disease and their clinical manifestations). Our group has previously shown that learning is improved with the use of an online scaffolded concept map in which students could "drag and drop" missing nodes into the appropriate place. The groups with access to the testable concept maps outperformed the control groups in both studies, and they were very favourable to the use of concept maps in this way. Further, automated individualised feedback possible with the testable pathogenesis maps appears to promote and maintain enthusiasm and interest without the usual deterrents of providing feedback manually (i.e., its time-consuming and labour-intensive nature) (Ho, Kumar, & Velan, 2014; Kumar, Dee, Kumar, & Velan, 2011).

Additional uses of concept maps in medicine

Although the heart of concept mapping and its most promising use is to encourage meaningful learning, it can be used in medical education in a variety of ways.

In the design of medical curricula, concept maps are able to display the network of relationships between concepts and highlight important themes, which a series of outlines may not be able to do as effectively. In this way, significant concepts can be prioritised in teaching, and content across disciplines can be integrated, removing possible redundancy. Concept mapping can help course designers conceptualise the subject matter in a more complete manner, thus allowing the succinct communication of a great deal of information from various disciplines (Edmondson, 1995). Similarly, concept mapping could provide an effective method through which different departments and disciplines could identify areas that would benefit from collaborative teaching. By integrating aspects of pathophysiology, pharmacology and other disciplines, as well as psychosocial factors, concept maps may encourage a multidisciplinary approach not only to learning, but ultimately also to patient care (Vink, Tartwijk, Bolk, & Verloop, 2015; Weiss, Levison, Donoghue, Hoffman, & Magrane, 2000).

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As mentioned previously, concept maps have been used in medical education as an assessment tool, particularly to encourage more holistic learning. While it is possible to use hand-drawn concept maps for this purpose, the logistical difficulties in assessing such maps and providing useful feedback mitigates against their use. As yet, there is no simple, widely available tool that enables this potential to be realised. There are also questions surrounding user acceptance and whether such assessments might underestimate students' proficiency by demanding a level of technical literacy that distracts them from knowledge-based mapping tasks (Weinerth, Koenig, Brunner, & Martin, 2014). Furthermore, the idiosyncratic nature of such maps raises difficulties in assessment (Daley & Torre, 2010). There is great variation between individuals in the way they organise information, even across experts within a narrow scholarly domain. The discrepancies in knowledge frameworks seem to be independent of problem-solving ability and hence complicate the process of assessing concept maps (McGaghie, McCrimmon, Mitchell, Thompson, & Ravitch, 2000).

Difficulties in broader use of concept maps

While there is increasing evidence that concept maps can be greatly beneficial for learning, it is not uncommon to encounter initial resistance from both students and instructors. In the midst of reports of positive experiences from students are contrasting reports that concept mapping can be perceived by students as requiring an unreasonable amount of time and effort (Pudelko, Young, Vincent-Lamarre, & Charlin, 2012). Given this resistance to changing learning and study methods, Torre et al. (2007) suggest that strategic use of concept mapping, based on students' need to integrate knowledge across disciplines, could minimise student opposition. Thus, the question remains of when and how concept mapping should be used within a particular context to maximise learning behaviours and outcomes (Pluta, Richards, & Mutnick, 2013). In the following discussion, we consider different contexts in which concept maps might be effective—namely, via use of scaffolded and self-constructed concept maps in appropriate contexts—and how learning benefits may vary based on learners' initial level of knowledge.

Scaffolded and self-constructed concept maps

The notion of concept mapping is not uniform and can mean different things to different people. Two main types of concept maps are currently used to promote learning. One requires students to construct their own maps by creating linking phrases between concepts, whereas the other (sometimes referred to as a "scaffolded approach") typically involves a teacher-designed template, which students complete. It should be noted that there are many variations possible in the degree of scaffolding provided, so concept maps could be seen as lying on a spectrum from entirely learner-centred (self-constructed) to predominantly teacher-guided (scaffolded). One demonstration of this concept is IKAS (intelligent knowledge assessment system), which allows students to alter the degree of difficulty (i.e., scaffolding) of a task. The simplest level involves simply inserting linking phrases from a list into a provided concept map structure, while students must create their own structure at the most

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difficult level. The presence or absence of a structure and whether concepts and/or linking phrases are provided or student-generated are variables allowed by this system (Anohina-Naumeca, Grundspenkis, & Strautmane, 2011).

Self-constructed concept mapping is a student-centred method that has been considered superior for several reasons (Yin, Vanides, Ruiz-Primo, Ayala, & Shavelson, 2005), including: (i) it more accurately reflects differences between students' knowledge structures, (ii) it provides more opportunities for demonstrating students' partial understanding and misconceptions, (iii) it provides students with more scope to reveal their understanding and (iv) it elicits more high-order cognitive processes. Yet, this method is typically met with the most resistance from students because self-constructed maps are more time-consuming to create and more likely to lead to cognitive overload (Chen, Chen, & Chen, 2013). The complexity of self-constructed maps also renders them more difficult to assess.

In contrast, scaffolded expert concept maps have been shown not only to provide a helpful introduction to the concept mapping process for students, but also to improve learning (Chang, Sung, & Chen, 2001; Ho et al., 2014). Heavily scaffolded maps are considered to be an instructor-driven, top-down method of learning. In a study that compared students' construction of their own maps, using either a paper-and-pencil or online method, the use of scaffolded maps resulted in higher performance in subsequent tests (Chang et al., 2001). Amongst a cohort of junior medical students, the use of a scaffolded drag-and-drop method of concept mapping was both effective for learning and readily accepted by students (Ho et al., 2014). This suggests that scaffolded maps may be helpful in lowering cognitive load, as well as enabling students to immediately focus on and learn key concepts and relationships.

Cognitive load theory assumes a limited working memory for novel information, whereby learning occurs through the organisation of new information into cognitive schemas in unlimited long-term memory. Cognitive load is comprised of the inherent load of what is to be learned, the load imposed by the manner in which information is presented, as well as the load used to produce and organise schema, and thus learn (Merrienboer & Sweller, 2010). So, if working memory is limited, then it is possible to hamper learning by presenting students with a learning task that requires unnecessary effort (de Jong, 2010). Schemes that help students store and organise information into long-term memory could reduce working load and therefore optimise learning in a way that promotes transfer and lifelong learning, enabling the learner to work in ill-defined ever-changing environments, handle decisions and cope with non-routine processes (Kirschner, 2002), all of which are expected of medical students. Accordingly, it is unsurprising that scaffolded maps, which present a framework for ideas and concepts, are advantageous.

O'Donnell et al. (2002) proposed that scaffolded maps are particularly beneficial for novices in a discipline in which they have little prior knowledge of a topic, who appear to benefit from the structure provided by maps. By summarising large amounts of information and providing students with an overview of processes, scaffolded concept maps provide a ready-formed structure and may accordingly accelerate learning. The

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scaffold provides instructional guidance when there is no underlying schema, helping students construct their own and providing a possible one (Kalyuga, Ayres, Chandler, & Sweller, 2003). Rendas et al. (2006) found that although students had difficulty constructing their own map, discussion of incomplete tutor maps was considered more useful and less time-consuming. Although minimally guided instruction is looked upon favourably from the constructivist perspective, in many ways, it can lead to disorganised understanding and misconceptions (Kirschner, Sweller, & Clark, 2006).

Nevertheless, it is possible that for more senior students, who have pre-existing discipline knowledge, scaffolded maps may actually conflict with their established knowledge frameworks and thus yield less benefit. As expertise in a subject increases, learning may be more efficient with less guided forms of instruction. Excessive description and information can not only be distracting and redundant, but also require more effort to process (Kalyuga, Chandler, & Sweller, 1998). It would therefore be of value to study the impact of scaffolded concept maps on the learning of senior medical students in comparison with a less structured approach, such as self-constructed maps, to determine the most effective and acceptable form of concept mapping for such students.

Online concept maps for assessment and feedback

For many educators, providing feedback forms a significant part of their workload. It is well established that feedback during the learning process, not simply at the end, is valuable for students' learning (Nicol & Macfarlane-Dick, 2006). At present, concept maps can be manually graded via a number of methods, all of which entail considerable investment of time and effort by teachers (Yin et al., 2005). However, since most concept mapping is performed online, there is hope for an automated system to provide students with the desired feedback and grades.

One current approach is automated evaluation of drag-and-drop versions of scaffolded concept maps. Due to their constrained nature, scaffolded maps can be more quickly and reliably assessed (Yin et al., 2005). Encouragingly, Chang et al. (2001) found those students working with scaffolded maps performed better in subsequent tests, possibly because this was associated with a lower cognitive load. It is of note that the immediate feedback these students received, compared to the other experimental conditions, fostered higher motivation to learn and positive attitudes to concept mapping. Similar student responses regarding instantaneous feedback were also noted by Wu, Hwang, Milrad, Ke and Huang (2012). Using a computerised program, students created concept maps from a predetermined set of concepts. On submission, an automated system provided feedback on any incorrect and missing connections, also presenting supplementary learning material related to the error. The experimental group was found to have significantly better progress and better attitudes towards learning than the control group (who used computerised concept mapping without the automated feedback mechanism). The authors also showed that immediate feedback enhanced student motivation as well as the process of learning through reflection and revision.

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Nevertheless, there is value in students constructing their own concept maps, which encourage the processing of material on a deeper and more individual level. Different automated methods have been tested and refined in an attempt to assess such maps, which would take a load off instructors, reducing the time needed to grade and to provide feedback to students. One example is Robograder, an automated computer-based system developed by Luckie, Harrison and Ebert-May (2011). However, in order for Robograder to function, instructors must first create a grading matrix by manually inputting all possible correct and incorrect concepts and propositions into a spreadsheet. While Robograder can be used without instructor involvement once the matrix is established, the initial workload would remain high, unsurprisingly. An alternative approach is a rule-based electronic evaluation system whereby students' maps are graded by comparing them to the instructor's "criterion" or "template" map (Cline, Brewster, & Fell, 2010). While this system showed a strong positive correlation with manually graded concept maps, the authors noted the importance of well-constructed instructor maps. For example, it is essential to use more specific labels for relationships (e.g., "produces by chemical means" rather than simply "produces") to avoid ambiguity (Cline et al., 2010). Even when limiting students to using a predetermined set of concepts, a "gold standard" or template map is essential to enable a grading system that compares students' maps to those created by instructors.

Both of the above examples also demonstrate that, currently, concept map grading software is unable to detect when a learner's choice of words does not precisely match the expert's preferred term but are still valid and correct, or when the inverse relationship is presented (e.g., "cows eat grass" rather than "grass is eaten by cows"). This could be improved with the development and use of a catalogue of relationships possible in concept maps, allowing the recognition of relationship symmetry and transitivity (Strautmane, 2014), or the incorporation of online dictionary and thesaurus software that can recognise synonyms and misspellings (Luckie et al., 2011).

An alternative system for assessing concept maps is AKOVIA (Automated Knowledge Visualisation and Assessment), developed by Ifenthaler (2014), a validated tool for automated assessment of web-based textual and graphical knowledge representations. AKOVIA is a web-based tool that can assess students' graphical knowledge representations by comparing them to an expert's conceptions, providing personalised and adaptive feedback. This model-based feedback tool aims to provide semantically and structurally sensitive graphical and text-based feedback that is personalised and adaptive. This might be a potentially effective and valid tool for providing students with feedback on self-constructed maps. Nevertheless, all of the aforementioned grading and feedback tools lack the simplicity desirable for wider use, and all require further testing and development.

Conclusion

Concept maps are graphical representations of knowledge that have been shown to promote meaningful learning, critical thinking and problem-solving skills. They have been found to be beneficial for learning in several contexts, including medical education;

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however, the use of concept maps in education overall, and medical education in particular, must still overcome several obstacles. We believe that studies exploring the best contexts in which to use scaffolded or self-constructed concept maps may help to alleviate some of these difficulties and may maximise the benefits gained. Furthermore, the development and validation of user-friendly automated tools for assessment and feedback of online concept maps would be of great value to both students and educators.

References

All, A. C., Huycke, L. I., & Fisher, M. J. (2003). Instructional tools for nursing education: Concept maps. *Nursing Education Perspectives*, *24*(6), 311–317.

Anohina-Naumeca, A., Grundspenkis, J., & Strautmane, M. (2011). The concept map-based assessment system: Functional capabilities, evolution, and experimental results. *International Journal of Continuing Engineering Education and Life Long Learning*, *21*(4), 308–327.

Ausubel, D. P. (1968). *Educational psychology: A cognitive view*. New York, NY: Holt, Reinhart & Winston.

Canas, A. J., Coffey, J. W., Carnot, M. J., Feltovich, P., Hoffman, R. R., Feltovich, J., & Novak, J. D. (2003). A summary of literature pertaining to the use of concept mapping techniques and technologies for education and performance support. Pensacola, FL: The Institute for Human and Machine Cognition.

Chang, K. E., Sung, Y. T., & Chen, S. F. (2001). Learning through computer-based concept mapping with scaffolding aid. *Journal of Computer Assisted Learning*, *17*(1), 21–33. doi:10.1111/j.1365-2729.2001.00156.x

Chen, H. H., Chen, Y. J., & Chen, K. J. (2013). The design and effect of a scaffolded concept mapping strategy on learning performance in an undergraduate database course. *IEEE Transactions on Education*, *56*(3), 300–307.

Cline, B. E., Brewster, C. C., & Fell, R. D. (2010). A rule-based system for automatically evaluating student concept maps. *Expert Systems with Applications*, *37*, 2282–2291.

Daley, B. J., Shaw, C. A., Balistrieri, T., Glasenapp, K., & Piacentine, L. (1999). Concept maps: A strategy to teach and evaluate critical thinking. *Journal of Nursing Education*, *38*(1), 42–47.

Daley, B. J., & Torre, D. M. (2010). Concept maps in medical education: An analytical literature review. *Medical Education*, *44*(5), 440–448. doi:10.1111/j.1365-2923.2010.03628.x

Daley, B. J., Torre, D. M., Stark-Schweitzer, T., Siddartha, S., Ziebert, M., & Petkova, J. (2006). *Advancing teaching and learning in medical education through the use of concept maps.* Paper presented at the Second International Conference on Concept Mapping, Universidad de Costa Rica, San Jose, Costa Rica.

de Jong, T. (2010). Cognitive load theory, educational research, and instructional design: Some food for thought. *Instructional Science*, *38*, 105–134.

ISSN 1442-1100

Edmondson, K. M. (1995). Concept mapping for the development of medical curricula. *Journal of Research in Science Teaching*, *32*(7), 777–793. doi:10.1002/tea.3660320709

Edmondson, K. M. (2005). Assessing science understanding through concept maps: A human constructivist view. In J. J. Mintzes, J. H. Wandersee & J. D. Novak (Eds.), *Assessing science understanding* (pp. 19–41). Burlington, MA: Elsevier.

Edmondson, K. M., & Smith, D. F. (1998). Concept mapping to facilitate veterinary students' understanding of fluid and electrolyte disorders. *Teaching and Learning in Medicine*, *10*(1), 21–33. doi:10.1207/s15328015tlm1001_5

Gonzalez, H. L., Palencia, A. P., Umana, L. A., Galindo, L., & Villafrade, L. A. (2008). Mediated learning experience and concept maps: A pedagogical tool for acheiving meaningful learning in medical physiology students. *Advances in Physiology Education*, *32*, 312–316.

Ho, V., Kumar, R. K., & Velan, G. (2014). Onine testable concept maps: Benefits for learning about the pathogenesis of disease. *Medical Education*, *48*, 687–697.

Ifenthaler, D. (2014). AKOVIA: Automated knowledge visualization and assessment. *Technology, Knowledge and Learning*, *19*(1–2), 241–248. doi:10.1007/s10758-014-9224-6

Kalyuga, S., Ayres, P., Chandler, P., & Sweller, J. (2003). The expertise reversal effect. *Educational Psychologist*, *38*(1), 23–31.

Kalyuga, S., Chandler, P., & Sweller, J. (1998). Levels of expertise and instructional design. *Human Factors*, *40*(1), 1–17. doi:10.1518/001872098779480587

Kanthan, R., & Mills, S. (2005). Active learning strategies in undergraduate medical education of pathology: A Saskatoon experience. *Journal of the International Association of Medical Science Educators*, *15*, 12–18.

Kirschner, P. A. (2002). Cognitive load theory: Implications of cognitive load theory on the design of learning. *Learning and Instruction*, *12*(1), 1–10. doi:10.1016/S0959-4752(01)00014-7

Kirschner, P. A., Sweller, J., & Clark, R. E. (2006). Why minimal guidance during instruction does not work: An analysis of the failure of constructivist, discovery, problem-based, experiential, and inquiry-based teaching. *Educational Psychologist*, *41*(2), 75–86. doi:10.1207/s15326985ep4102_1

Kumar, S., Dee, F., Kumar, R., & Velan, G. (2011). Benefits of testable concept maps for learning about pathogenesis of disease. *Teaching and Learning in Medicine*, *23*(2), 137–143.

Luckie, D., Harrison, S. H., & Ebert-May, D. (2011). Model-based reasoning: Using visual tools to reveal student learning. *Advances in Physiology Education*, *35*(1), 59–67.

McGaghie, W. C., McCrimmon, D. R., Mitchell, G., Thompson, J. A., & Ravitch, M. M. (2000). Quantitative concept mapping in pulmonary physiology: Comparison of student and faculty knowledge structures. *American Journal of Physiology: Advances in Physiology Education*, *23*(1), 72–81.

ISSN 1442-1100

Merrienboer, J. J., & Sweller, J. (2010). Cognitive load theory in health professional education design principles and strategies. *Medical Education*, *44*, 85–93.

Mok, C. K. F., Whitehill, T. L., & Dodd, B. J. (2008). Problem-based learning, critical thinking and concept mapping in speech-language pathology education: A review. *International Journal of Speech-Language Pathology, 10*(6), 438–448. doi:10.1080/17549500802277492

Nicol, D. J., & Macfarlane-Dick, D. (2006). Formative assessment and self-regulated learning: A model and seven principles of good feedback practice. *Studies in Higher Education*, *31*(2), 199–218. doi:10.1080/03075070600572090

Novak, J. D. (1990). Concept maps and Vee diagrams: Two metacognitive tools to facilitate meaningful learning. *Instructional Science*, *19*(1), 29–52. doi:10.1007/bf00377984

Novak, J. D., & Canas, A. J. (2008). *The theory underlying concept maps and how to construct and use them*. Retrieved from http://cmap.ihmc.us/Publications/ResearchPapers/TheoryUnderlyingConceptMaps.pdf

O'Donnell, A. M., Dansereau, D. F., & Hall, R. H. (2002). Knowledge maps as scaffold for cognitive processing. *Educational Psychology Review*, *14*(1), 71–86.

Pintoi, A. J., & Zeitz, H. J. (1997). Concept mapping: A strategy for promoting meaningful learning in medical education. *Medical Teacher*, *19*(2), 114–121. doi:10.3109/01421599709019363

Pluta, W. J., Richards, B. F., & Mutnick, A. (2013). PBL and beyond: Trends in collaborative learning. *Teaching and Learning in Medicine*, *25*(Suppl. 1), S9–S16. doi:10.1080/10401334.2013.842917

Pudelko, B., Young, M., Vincent-Lamarre, P., & Charlin, B. (2012). Mapping as a learning strategy in health professions education: A critical analysis. *Medical Education*, *46*(12), 1215–1225.

Rendas, A. B., Fonesca, M., & Pinto, P. R. (2006). Toward meaningful learning in undergraduate medical education using concept maps in a PBL pathophysiology course. *Advances in Physiology Education*, *30*, 23–29.

Saeidifard, F., Heidari, K., Foroughi, M., & Soltani, A. (2014). Concept mapping as a method to teach an evidence-based educated medical topic: A comparative study in medical students. *Journal of Diabetes & Metabolic Disorders*, *13*(86).

Strautmane, M. (2014, June). *Increasing the flexibility of automated concept map based knowledge assessment.* Paper presented at the International Conference on Computer Systems and Technologies, Ruse, Bulgaria.

Surapaneni, K. M., & Tekian, A. (2013). Concept mapping enhances learning of biochemistry. *Medical Education Online*, *18*, 1–4.

Torre, D. M., Daley, B. J., Stark-Schweitzer, T., Siddartha, S., Petkova, J., & Ziebert, M. (2007). A qualitative evaluation of medical student learning with concept maps. *Medical Teacher*, *29*, 949–955.

ISSN 1442-1100

Veronese, C., Richards, J. B., Pernar, L., Sullivan, A. M., & Schwartzstein, R. M. (2013). A randomized pilot study of the use of concept maps to enhance problem-based learning among first-year medical students. *Medical Teacher*, *35*(9), e1478–e1484.

Vink, S. C., Tartwijk, J. V., Bolk, J., & Verloop, N. (2015). Integration of clinical and basic sciences in concept maps: A mixed-method study on teacher learning. *BMC Medical Education*, *15*(20).

Watson, G. R. (1989). What is concept mapping? *Medical Teacher*, *11*(3–4), 265–269.

Weinerth, K., Koenig, V., Brunner, M., & Martin, R. (2014). Concept maps: A useful and usable tool for computer-based knowledge assessment? A literature review with a focus on usability. *Computers and Education*, *78*, 201–209.

Weiss, L. B., Levison, S. P., Donoghue, G. D., Hoffman, E., & Magrane, D. (2000). Tools for integrating women's health into medical education: Clinical cases and concept mapping. *Academic Medicine*, *75*(11), 1081–1086.

Wilgis, M., & McConnell, J. (2008). Concept mapping: An educational strategy to improve graduate nurses' critical thinking skills during a hospital orientation program. *The Journal of Continuing Education in Nursing*, *39*(3), 119–126.

Willis, S. C., Jones, A., Bundy, C., Burdett, K., Whitehouse, C. R., & O'Neill, P. A. (2002). Small-group work and assessment in a PBL curriculum: A qualitative and quantitative evaluation of student perceptions of the process of working in small groups and its assessment. *Medical Teacher*, *24*(5), 495–501. doi:10.1080/01421590210000012531

Wu, P. H., Hwang, G. J., Milrad, M., Ke, H. R., & Huang, Y. M. (2012). An innovative concept map approach for improving students' learning performance with an instant feedback mechanism. *British Journal of Educational Technology*, *43*(2), 217–232. doi:10.1111/j.1467-8535.2010.01167.x

Yin, Y., Vanides, J., Ruiz-Primo, M. A., Ayala, C. C., & Shavelson, R. J. (2005). Comparison of two concept-mapping techniques: Implications for scoring, interpretation and use. *Journal of Research in Science Teaching*, *42*(2), 166–184.

ISSN 1442-1100