A metacognitive tool: Theoretical and operational analysis of skills exercised in structured concept maps ☆

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Abstract
Developing meaningful learning is not only difficult to achieve but also time consuming, because it requires a large number of different skills to develop and master. Many studies have shown that organizing knowledge in concept maps helps teachers and students to develop such a meaningful learning (Nesbit, J.C., Adescope, O.O., 2006. Learning with concept and knowledge maps: a meta-analysis. Rev. Educ. Res. 76:3, 413-446). Based on the work of Tyler (Tyler, R.W., 1950. Basic principles of Curriculum and Instruction. University of Chicago Press, Chicago, IL) and Anderson (Anderson, L.W., Krathwohl, D.R., Airasian, P.W., Cruikshank, K.A., Mayer, R.E., Pintrich, P.R., Raths, J., Wittrock, M.C., 2001. A Taxonomy for Learning, Teaching, and Assessing: A revision of Bloom's Taxonomy of Educational Objectives. Longman, New York), this study proposes to characterize and to organize precisely, rigorously, and operationally in a two-dimensional matrix, the skills exercised during the elaboration of concept maps, here referred to as context-dependent and hierarchically structured concept maps (sCM). These skills correspond to those actually needed in transfer of knowledge, and the matrix could be used as an instructional tool to assist learners and teachers in this transfer. In addition it allows them to pay attention to the cognitive processes and types of knowledge involved during sCM elaboration. Making explicit the taxonomic levels of cognitive efforts implemented while organizing knowledge in a concept map could constitute a useful metacognitive tool to focus the teachers and learners' attention and efforts towards achieving higher-order thinking skills and meaningful learning.

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Introduction

With the development of the World Wide Web, knowledge has become easily accessible to most people in all fields. Accompanying this accessibility, new constraints emerged for both teachers and learners: finding appropriate information on one hand and constructing meaningful knowledge within this wheat of information on the other hand. Indeed, once the information found, it still remains to verify their truthfulness, and to be able to link them together in order to construct, in precise, logic and explicit ways, a solid and reliable framework of knowledge. This requires understanding, analyzing, and evaluating what has been learned, and corresponds to a high degree of scientific expertise and advanced thinking skills. Teachers sometimes emphasize on memorizing information or specific terms (Mayer, 2002). Acquisition of knowledge is important, but not sufficient, and another essential goal in education is to promote the ability to use what has been learned (transfer) (Mayer, 2002; Mestre, 2002). Transfer of knowledge indicates meaningful learning (Mayer, 2001, 2002; Haskell, 2001). It requires learners not only to remember what they have learned, but also to solve new problems, answer new questions or facilitate learning of new matter in a different context. Such a meaningful learning is difficult to achieve because it requires multiple cognitive steps: retention, active and purposeful retrieval of specific terms or relevant concepts from long term memory and elaboration, differentiation, and integration of those concepts in organized cognitive structure (Atkinson and Shiffrin, 1968; Terry, 2006; Mintzes et al., 2005b; Karpicke, 2012). Based on Ausubel's learning theory (Ausubel, 1968), the key idea in meaningful learning is that the learner has to integrate gradually, through the mechanism of subsumption, new pieces of knowledge within existing pathways in his own cognitive structure (Mintzes et al., 2005a). In this perspective, concept map (CM)—tools representing knowledge in maps in which new material can be added—can help students to structure ideas and progressively construct mental representations of abstracts and complex concepts (Novack, 2008). Indeed, numerous studies (Nesbit and Adescope, 2006, and references therein) have shown that organizing knowledge in CM helps teachers and students to develop meaningful learning.

A CM is a graphical tool used to organize and represent knowledge (Novak and Cañas, 2006). In CM, concepts are enclosed within circles or boxes, and linked to each other by directed connecting lines. Words on the lines, or connectors, specify the relationship between the related concepts. An important characteristic of CM is that concepts are represented in a hierarchical way with the most inclusive and general concepts at the top of the map and the more specific and less general once located below. In addition, the presence of "cross-links" on CM highlights relationships between distant concepts in different segments or domains of the CM. These cross-links often represent new and thus creative links from the CM designer, highlighting a complex and integrated knowledge. Specific examples or objects that help clarifying the meaning of a given concept can be included in the CM. These are usually not written in boxes since they do not represent concepts. According to their founder, they are sometimes called "Novakian map" (Davies, 2011). Constructing such Novakian maps is difficult

to achieve and the hierarchical polarity described above is not always observed. A qualitative approach analyzing student's concept maps highlighted three major patterns referred to as "spoke", "chain" and "net" structures (Kinchin et al., 2000). For a given scientific content represented, these maps differ in terms of complexity. An increased integration of pieces of knowledge is observed from spoke to net structures. A spoke structure contains only one hierarchical level and very simple associations, whereas a chain structure represents different levels of hierarchy, but often incorrect. In a net structure, elements are connected to each other and reflect complexes interactions at different conceptual levels and indicate meaningful learning (Kinchin et al., 2000; Kinchin, 2008). Similar representations have been observed in our practice over 5 years with learners in science classrooms in secondary school in Switzerland (aged from 13 to 20 years), as well as with student science teachers at the postgraduate or undergraduate level in University (pre-service science teacher training), both in Fribourg and Geneva (unpublished results; Racenet and Chevron, 2013). In a Novakian map, the hierarchical structure for a particular domain of knowledge depends on the context in which knowledge is considered, and a suitable way to clearly specify the domain to be explored is to construct a CM with reference to a focus question the CM seeks to answer (Novak and Cañas, 2006; Davies, 2011). Indeed, depending on a particular context, pieces of knowledge presented in a CM will be differentially organized. For example, a specific term like "DNA" can be related to different terms, whether describing cell function, DNA replication or heredity. Another important difficulty is to make choices, thus establishing priorities on the scientific notions, facts or concept being present on the map (Novak, 2008; Novak, 2010; Novack and Cañas, 2006). We also observed that CM designers strain to delimitate the domain to be explored. Indeed, when a focus question is presented to learners (students or student teachers), they tend towards deviating from the focus question and constructing maps related to a complete domain of knowledge, and rarely answer the asked question. Finally, a lack of rigor is observed to precisely define the relationships among elements inside CM (Kharatmal and Nagarjuna, 2010).

In this study, in order to explain and overcome the observed difficulties in constructing hierarchically organized CM, here referred to as "Context-dependent structured CM" (sCM), sCM related skills have been categorized in an explicit and operational way. Making explicit the taxonomic levels of cognitive efforts implemented while organizing knowledge in maps appears as an interesting metacognitive tool to focus learner attention and efforts towards achieving higher-order thinking skills. The sCM matrix, described in detail in the next section, is proposed to help, guide, and invite both teachers and learners for transfer in knowledge and thus meaningful learning.

Structured concept map (sCM)

I have used the Tyler matrix (Tyler, 1950) and the revised Bloom taxonomy (Anderson et al., 2001; Krathwohl, 2002), the latter proposing to organize in a two-dimensional table four major types of knowledge and six cognitive process

categories. The four major types of knowledge are Factual knowledge, Conceptual knowledge, Procedural knowledge and Metacognitive knowledge. The six cognitive categories are to *Remember*, *Understand*, *Apply*, *Analyze*, *Evaluate* and *Create*. Briefly, the four types of knowledge dimension are organized from more "concrete" to more "abstract" knowledge. *Factual knowledge* corresponds to the basic elements (terminology and specific details) students must know "to be acquainted with a discipline or to solve problems in it". *Conceptual knowledge* corresponds to classifications and categories, principles and generalizations, theories, models and structures. *Procedural knowledge* relates to "how to do something" (techniques, methods, criteria for determining when to use appropriate procedures). Finally, *Metacognitive knowledge* involves cognition in general as well as awareness on its own cognition. The cognitive processes are organized as a continuum of increasing cognitive complexity: *Understand* is believed to be more cognitively complex than *Remember*; *Analyze* more cognitively complex than *Apply*, and so. As mentioned (Anderson et al., 2001), *Remember* consists in "retrieving relevant knowledge from long term memory". *Understand* corresponds to cognitive efforts made to "elaborate meaning from oral, written or graphic educational messages". *Understanding* can be observed through activities like exemplifying (illustrating), classifying (subsuming), inferring, comparing (mapping, matching), or explaining (constructing models). *Apply* consists in "executing a procedure to a familiar task (executing) or to an unfamiliar task" (implementing). *Analyzing* consists in "breaking material into its constituent parts and determine how the parts relate to each one another and to an overall structure or purpose". It can be further divided into 3 sub-categories: discriminating (focusing, selecting); organizing (finding coherence, integrating, outlining, parsing, and structuring); attributing (deconstructing). *Evaluate* concerns "the ability to make judgments based on criteria and standards" (checking, judging). And finally *Create* consists in "organizing elements together to form a coherent or functional whole" or in "reorganizing elements into a new pattern or structure". Creation appears while generating hypothesis, planning (designing a procedure to accomplish a task) and producing (constructing).

Operational analysis of skills exercised in structured concept maps using the revised taxonomy of Andersen and Krathwohl

This taxonomy allows to categorize the skills exercised during the construction of sCM and to propose the sCM matrix. To answer a given focus question in a sCM, learners must go through the following steps (see Table 1). (1) *Recognizing and recalling*: actively retrieve the appropriate terminology used to specify details, elements, and concepts. (2) *Remembering*: remember principles, generalizations, theories or models. (3a) *Remember* and (3b) *understand* the strategic skills for organizing knowledge in maps. (4) *Illustrating/explaining*: find appropriates examples, figures or pictures to illustrate their map. (5) *Subsuming/mapping/constructing models*: connect elements together. This fundamental task while elaborating a CM forces the CM designer to construct

meaning and elaborate models. (6) *Selecting*: while thinking and discussing the elaboration of the model, they have to distinguish relevant from irrelevant, or important from less important, elements to answer the focus question. (7a) *Discriminating*: identify the relative importance of relevant elements to elaborate a hierarchical structure and select the core concept. (7b) *Structuring*: determine how elements connect to each other to construct the core concept and to answer the focus question. (3c) *Implementing*: since they draw a map to answer a particular question, they have to apply the procedure to an unfamiliar task. (8a) *Integrating*: organize and link different elements in a hierarchical structure. (8b) *Outlining*: use different colors, type or size of character to outline a particular point. (9) *Hypothesizing*: organizing and connecting elements and concepts in a first draft of sCM, connecting concepts of different domains on the sCM or from another field of knowledge to improve the considered knowledge (cross-links). (10) Judge the relevance of the terminology used. (11) *Judgments based on criteria/checking*: precisely name the links between elements and carefully consider the established links to answer the focus question. (12) *Judging*: while doing steps 10/11, sCM designers detect inconsistencies in the knowledge structure. Steps 9 to 12 correspond to high levels in the cognitive process dimension. Likewise, proposing an organization among different elements to answer a focus question is difficult to achieve and forces transfer in learning. (13) *Hypothesizing/designing*: after careful consideration, sCM designers must reorganize elements to better represent knowledge in an original and new way to answer the focus question. This corresponds to high taxonomic level of procedural knowledge. Using the proposed matrix and helped by teachers, learners can develop *metacognitive knowledge* through the last following steps. (14a) Understand the contribution of sCM in metacognition development. (14b) Get aware of the cognitive demand of the different tasks exercised in sCM. (14c) Assess the relevance of the tool used to answer the focus question. (14d) Step back and be aware of the evolution of one's own representation and functioning. All these steps in elaborating sCM are depicted in Table 1.

An example of sCM construction answering the focus question in chemistry: "What is the composition of matter?" is given as example (Fig. 1). The tasks exercised during its construction are presented in Table 2.

In order to highlight the evolution in knowledge structure observed when using sCM matrix, a work proposed by a student teacher on photosynthesis is given (Figs. 2 and 3).

The first CM draft (Fig. 2) was performed by the student teacher aiming to document photosynthesis. One can observe the absence of hierarchy, some missing essential elements (like chloroplasts and green plant), repeated terms. In addition, connectors are not adequately defined. The second map was performed by the same student teacher using the sCM matrix under supervision (Fig. 3). Hierarchy is now clearly established, the core concepts are identified, essential elements to answer the focus question are present on the map with adequate terminology and appropriate connectors are used. We observe that the concept of "cellular respiration" is present on the map. It is not required to answer the focus question, but nevertheless indicates more integrated and complex learning.

Table 1 Operational analysis of skills exercised during sCM construction.

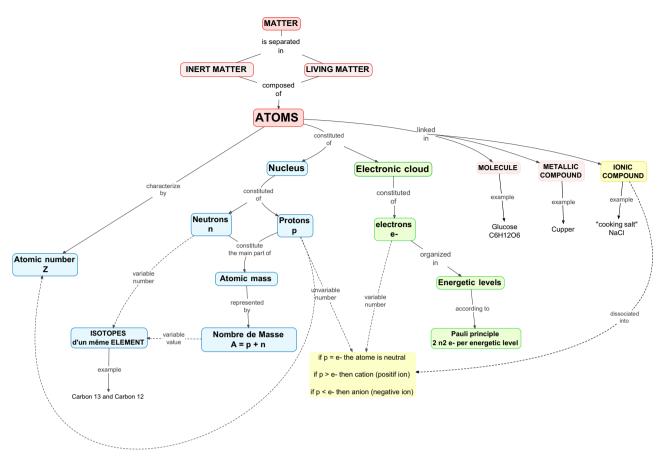| The knowledge dimension	The cognitive process dimension					
	Remember	Remember	Apply	Analyze	Evaluate	Create
Factual knowledge	**1** *Recognizing, recalling* Using appropriate terminology to name specific elements or concepts	**4** *Illustrating, explaining* Using the appropriate examples, figures, pictures		**6** *Selecting* Distinguish relevant from irrelevant or important from non important elements to answer the focus question	**10** *Judging* Judge the relevance of the terminology used	
Conceptual knowledge	**2** *Remembering* Remember principles, generalizations, theories and models	**5** *Subsuming, Mapping, Constructing knowledge's structure* Connecting elements in order to construct models		**7a** *Discriminating* Identify the relative importance of relevant elements to elaborate a hierarchical structure; identify the core concept; **7b** *Structuring* Determine how elements connect to each other to construct the core concept and to answer the focus question	**11** *Judgment based on criteria/checking* Precisely name the relation between elements; judge the relevance of the established links to answer the focus question	**9** *Hypothesizing* Organize elements in a first draft of sCM to form a coherent and functional whole answering the focus question; connect concepts of different domains on the sCM or from another field of knowledge to improve the considered knowledge. Name these creative links
Procedural knowledge	**3a** Remember the procedure of sCM construction (name elements in boxes, draw directed links, name the directed links)	**3b** *Strategic knowledge* Understand the procedure used to organize knowledge in map	**3c** *Implementing* Apply the procedure of sCM construction to an unfamiliar task	**8a** *Integrating* Organize and connect different elements in a hierarchical structure **8b** *Outlining* Use different colors, type or size of characters to outline a particular point	**12** *Judging* Evaluate and detect inconsistencies in the knowledge's structure	**13** *Hypothesizing, Designing* Suggest a reorganization in space to better represent knowledge; reorganize in space the different elements in an original and new way, to answer the focus question
Metacognitive knowledge	**14a** Understand the contribution of sCM in metacognition development		**14b** Get aware of the cognitive demands of the different tasks exercised to construct a sCM in a specific field of knowledge		**14c** Assess the relevance of the tool used on its own learning	**14d** Step back and be aware of the evolution of one's own representation; being aware of one's own functioning

Fig. 1 sCM answering the focus question in chemistry: "What is the composition of matter?"

Discussion

Based on the taxonomy proposed by Krathwohl and co-workers, this study proposes a precise, rigorous, and operational characterization of skills exercised during the elaboration of context-dependent and hierarchically structured concept maps. As described above, this is an instructional and metacognitive tool proposing a possible path for knowledge construction. In addition it allows sCM designers to pay attention to the cognitive processes and types of knowledge involved during the process of sCM elaboration.

As described, organizing sCM requires acquisition of specific terms, adequate exemplifying, explaining and comparing different scientific notions, terms or concepts. In addition, learners have to reorganize and connect elements together (transfer of knowledge) to answer a particular new focus question. During this process, skills of different taxonomic levels are exercised. Most of them correspond to high order thinking skills and involve complexes cognitive processes. The cognitive efforts required to develop these are hard to achieve. Constructing sCM is rarely a purely individual task, but rather engages both students and teachers in an active cognitive processing (Novak, 2010; Nesbit and Adescope, 2006). Indeed, it forces them to pay attention to and discuss between peer students, peer student-teachers or peer expert teachers, which information to keep as relevant, how to graphically integrate it into existing knowledge and which connector will be used, in order to precisely answer the focus question. As observed in

psychology (Duro et al., 2013) or in medical courses (West et al., 2000), whilst people advocate the value of their choices to connect any particular concept with one other in a specific way, or to choose specific concept or connecting word, meaningful learning is fostered in general, and critical thinking in particular. For all these reasons, the process of map construction is at least as important as the final product (Kinchin, 2008), and "the benefits of spending time on integrating prior understanding are likely to exceed the benefits of acquiring new knowledge that mainly remain isolated and unconnected" (Kinchin, 2010). This point is fundamental and served as the basis in elaboration of sCM matrix. The tasks learner accomplish when constructing sCM helps them to move from a linear knowledge to a structured network. This evolution in the structure of knowledge allows threshold concepts to emerge (Kinchin, 2010). To construct structured knowledge different teaching methods promoting meaningful learning are proposed (Ivie, 1998; Karpicke, 2012; Nesbit and Adescope, 2006). Among them, recent work addressed the question of which of the learning methods—active retrieval or CM elaboration—is the most powerful to achieve meaningful learning (Karpicke and Blunt, 2011; Mintzes et al., 2011). Retrieval is a process using available cues to actively reconstruct knowledge. It improves ability to retrieve knowledge again in the future and enhance learning (Karpicke, 2012; Roediger and Karpicke, 2006; Karpicke and Roediger, 2008). Multiples elements have to be recalled and integrated repeatedly while meaning develops. Depending on a particular time

Table 2   SCM matrix corresponding to the elaboration of the sCM "What is the composition of matter?".

The knowledge dimension	The cognitive process dimension					
	Remember	Remember	Apply	Analyze	Evaluate	Create
Factual knowledge	**1** *Name specific terms*: inert/living matter, atom, nucleus, electronic cloud, electron, proton, neutron, atomic mass (*A*), atomic number (*Z*), isotope, cation, anion, ionic compound, metallic compound, molecule, energetic level	**4** Give examples of ionic and metallic compounds, molecules and isotopes. Possibly provide images		**6** Distinguish relevant from irrelevant or important from non important elements to answer the focus question	**10** Judge the relevance of the terminology used	
Conceptual knowledge	**2** Remember principles, theories, models: atomic theory, Pauli principle, theories about atomic links (ionic, covalent)	**5** Link the different elements to understand the concepts of matter and atom		**7** Identify the relative importance of relevant elements to elaborate a hierarchical structure: Identify the core concept: matter, atom. Determine how elements connect to each other to construct the core concept and to answer the focus question: "What is the composition of matter?"	**11** Precisely name the relation between elements. For example: is organized in, is composed by, are characterized by... Judge the relevance of the established links to answer the focus question	**9** Organize elements in a first draft of sCM to form a coherent and functional whole answering the focus question. For example: proton, electron, neutron are on a same level. Connect concepts of different domains on the sCM or from another field of knowledge to improve the considered knowledge. For example: ionic compound linked to proton and electron (notions of cation/anion). Name these creative links
Procedural knowledge	**3a** Remember the procedure of sCM construction	**3b** Understand the procedure to organize knowledge in map	**3c** Apply the procedure of sCM to the elaboration of matter and atom models	**8** Organize and connect different elements in a hierarchical structure. For example: matter/ molecule/atom/ nucleus... Use different colors, type or size of characters to	**12** Evaluate and detect inconsistencies in the knowledge's structure	**13** Suggest a reorganization in space to better represent knowledge; reorganize in space the different elements in an original and new way, to answer the focus question

Table 2 (*continued*)

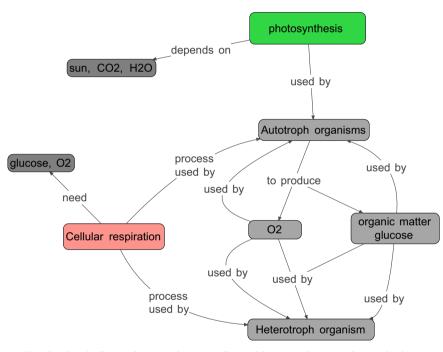| The knowledge dimension	The cognitive process dimension					
	Remember	Remember	Apply	Analyze	Evaluate	Create
Metacognitive knowledge		**14a** Understand the contribution of sCM in metacognition development		outline a particular point **14b** Get aware of the cognitive demands of the different tasks exercised to construct a sCM in a specific field of knowledge	**14c** Assess the relevance of the tool used on its own learning on matter and atom	**14d** Step back and be aware of the evolution of one's own representation; being aware of one's own functioning

Fig. 2 CM draft on photosynthesis performed by a student teacher in biology.

during the learning path to built well-constructed knowledge networks in memory, cognitive activity oscillates permanently between coding, active retrieval and integrating what has to be learned in a new, or existing framework (Terry, 2006; Karpicke and Roediger, 2008; Fischer, 2008). Since appropriate terminology is needed for integration in connected network of terms, a solid mental representation of a core concept may favor later on, purposeful retrieval and shrewd integration in memory of specific concepts. In the sCM approach, coding, retrieval and CM construction complement each other and this allows combining multiple learning goals (factual, conceptual, and metacognitive) both for learning and assessment (Tyler, 1950; Harden, 2002; Krathwohl, 2002). Moreover, making explicit the taxonomic levels of cognitive efforts implemented while organizing knowledge in maps provides a useful metacognitive tool to focus learners' attention and efforts towards achieving higher-order thinking skills. This supportive role of metacognitive knowledge in learning, teaching and assessing has been demonstrated (Veenman et al., 2006). Three principles have been shown for successful metacognitive instruction: "embedding metacognitive instruction in the content matter to ensure connectivity; informing learners about the usefulness of metacognitive activities to make them exert the initial extra effort; and prolonged training to guarantee the smooth and maintained application of metacognitive activity" (Veenman et al., 2006). Veenman referred to these principles as WWW&H rule (what to do, when, why, and how). Concerning this particular aspect, the sCM matrix could invite and help both teachers
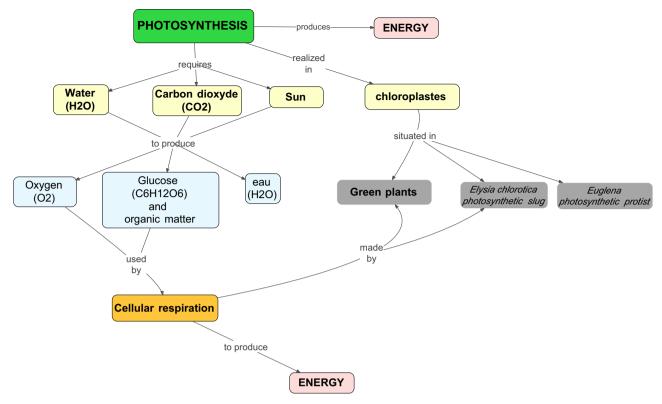
Fig. 3 sCM on photosynthesis, performed by the same student's teacher using the sCM matrix and answering the focus question in biology: "What is needed for photosynthesis to occur and what is produced?"

and students to develop such metacognitive skills. The sCM matrix is presented here to encourage wider debate about its theoretical underpinnings for future work, in particular in view of ongoing experimental tests in classrooms in Gymnase intercantonal de la Broye (Payerne, Switzerland) by a group of expert teachers in French, philosophy, history, music, physics, chemistry, biology and mathematics involved in a project of meaningful learning.

Conflict of interest statement

The author has no conflict of interest.

Acknowledgments

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