Implications of Parallels in Ausubelian Ideas of Meaningful Learning, Concept Mapping, and Recent Studies in Neurobiology, Especially as Related to Learning in Science and Cognate Disciplines

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ABSTRACT — Emergence of cognitive theories in mid-twentieth century initiated a major reform in the learning sciences and education; notably among them, the meaningful learning theory of David Ausubel. This is a synthesis of two historical strands, i.e. application of Ausubelian theory to teaching and learning, especially the invention and application of concept maps, and recent advances in application of the neurosciences to better understand human information processing and educational practices. Particular attention is given to elucidating the possible brain correlates of Ausubelian principles of learning and likely relationships of brain structure and function to education as represented by modern neuroscientific research and current derived theories, especially focusing on the teaching and learning of the sciences and cognate disciplines. Recommendations are made for further possible research on concept mapping and networking in memory using modern methods of brain imaging and analysis. Concept maps might serve as a kind of "Rosetta Stone" to assist in the interpretation of neurobiological images taken as individual's perform specific learning and recall tasks.

INTRODUCTION

Modern principles of teaching and learning have drawn extensively on evidence from the learning sciences, especially cognitive science and its applications. We present a historically-based analysis of the contribution of Ausubelian theory to learning, especially the derivative invention of mind mapping tools, particularly concept maps, including current perspectives on the use of concept maps in teaching and learning within a neuroscientific perspective, drawing especially from recent advances in applying the neurosciences to teaching and learning of abstract content such as science and cognate disciplines. Of necessity, the review is focused on published literature relevant to this particular synthesis, and we recognize that a broader base of recent scholarship has been devoted to the expanding field of neuroscience and education, some of it published especially in this journal.

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KEY PRINCIPLES OF AUSUBEL'S COGNITIVE LEARNING THEORY

David Ausubel (1963) published his assimilation theory of cognitive learning and established a new paradigm at a time when American psychology was overwhelmingly dominated by Skinner's behavioral psychology. Thus, the reception of Ausubel's theory was limited. However, Novak's research team at Purdue University found Ausubel's theory to be exactly what was needed to advance research in science education, and later in all disciplinary areas (e.g., Novak, 1977). Ausubel's theory spoke directly to how humans acquire and use new concepts and make new relationships among concepts. Ausubel (1963, 1968, Ausubel, Novak & Hanesian, 1978) stated seven basic principles that describe how humans learn new concepts and propositions, subsequently extended by Novak (1993) as described briefly below.

In Ausubel's cognitive psychology, the primary things that the learner learns are new concepts and propositions as further refined by Novak's team. *Concepts* are perceived regularities or patterns in events or objects, or in records of events or objects, designated by a label, which is usually a word. *Propositions* are two or more concepts connected with words to form a meaningful statement. Propositions are the primary units of meaning that need to be acquired. Meaningful learning can occur by two means: Reception learning and discovery learning. In reception learning, the learner is guided to observe the criterial attributes of new concepts and propositions, whereas in discovery learning the learner must identify and learn the criterial attributes, the latter is most characteristic of early childhood learning. But, after the child learns to speak, reception learning becomes the dominant form of learning for acquisition of new concepts and propositions.

The two most fundamental ideas in Ausubel's theory are the distinctions between rote learning and meaningful learning. In *rote learning*, the learner makes little or no effort to integrate new concepts and propositions with relevant existing concepts and propositions in her/his cognitive structure. In *meaningful learning***,** the learner makes a deliberate effort to integrate new concepts and propositions with existing relevant concepts and propositions in her/his cognitive structure. For meaningful learning to occur, three requirements must be met: (1) The material to be learned must be potentially meaningful, with a clear concept and propositional structure. (2) The learner must possess some relevant concepts and propositions into which the new concepts and propositions can be subsumed. (3) The learner must choose to seek to integrate the new concepts and propositions into her/his existing relevant concepts and propositions. While the teacher and curriculum planner can directly influence conditions one and two, she/he can only indirectly influence the third condition by selecting appropriate instructional and assessment strategies. In meaningful learning, frequently there are also concomitant motor and affective experiences, and these become subtle features of the concepts and propositions learned.

Ausubel's principle of *subsumption* holds that when a learner incorporates new concepts and propositions into her/his cognitive structure, both the new concept or proposition and the existing subsuming concept or proposition becomes modified. Thus a new cognitive entity is formed that is more than just the original idea plus the new idea; the synthesis leads to further differentiation of original subsumer. Ausubel refers to this successive assimilation of concepts or propositions in meaningful learning as *progressive differentiation*, where there has been further refinement of the original idea, often leading to a refined understanding of the nuances of the subsumer and its associated entities. The process of progressive differentiation of a concept can also result in *obliterative subsumption***,** where some subordinate concepts or propositions can no longer be recalled, for example if they were subsumed within a less-meaningful association with the subsuming more general idea.

The sixth principle in Ausubel's theory is *superordinate learning*. Although most meaningful learning occurs through the process of subsumption, occasionally a new concept may be learned that incorporates the ideas in two or more concepts or propositions, thus forming a new superordinate concept. For example, a child who learns that dogs, cats, cows and all animals that have fur and nurse their young via the female mammary glands are called mammals, this would be an example of superordinate learning. Although this form of learning occurs less frequently than subsumption, the power that superordinate concepts have for facilitating future meaningful learning in this domain are enormous. In fact, excellent curriculum planning should be explicitly designed to assure that the major superordinate ideas in a discipline are learned to some degree as soon as possible, for they confer such important facilitation of learning in this domain. Of course, further differentiation of superordinate concepts may occur over a lifetime. In the sciences, evolution, gene, entropy, conservation, particulate nature of matter, and similar concepts are examples of powerful superordinate concepts.

The seventh principle in Ausubel's theory is *integrative reconciliation*. As meaningful learning progresses, the meanings of concepts and propositions held by the learner undergo further modification, refinement, inclusiveness, or delineation of relevant details, and their distinction from closely related ideas. For major concepts in any discipline, integrative reconciliation occurs over the lifetime of the learner as more explicit subordinate ideas and propositions are subsumed into more general concepts and propositions, and ideas that may have appeared conflicting are reconciled under the more comprehensive concepts and propositions. In some respects, integrative reconciliation is the most important idea in Ausubel's assimilation theory, because it ties together all other principles of meaningful learning. For example, some obliterative subsumption of more detailed concepts and propositions may enhance the prominence and salience of key superordinate ideas in the learner's thinking. While acquisition of subordinate ideas is important in building expertise, the thing that distinguishes the expert from the novice is the quantity and quality of the "big ideas" they have developed. Similarly, the virtuoso musician not only plays the notes well, but they transmit feelings and emotions that capture the audience in an extraordinary way.

THE INVENTION & USE OF CONCEPT MAPS

In 1971, Novak's research group at Cornell University began a twelve-year longitudinal study that involved the use of 28 audio-tutorial science lessons with 191 students in Grades 1 and 2 using interview protocols for assessment. A control group of 48 students, enrolled in the same classrooms with the same teachers one year later, was also tested using the same interviews. Samples of the same instructed and uninstructed groups were interviewed periodically through Grade 12. Although the interviews showed that the students were gaining understanding of the science concepts presented, it was difficult to identify specific changes in children's ideas from the interview transcripts. Some method of evaluation was needed that would identify specific changes in children's concept and propositional knowledge regarding the science taught.

Building on the epistemological view that the learner's creation of science concepts and principles were the key to understanding science, and Ausubel's psychological ideas that meaningful learning led to understanding of science concepts and propositions, Novak's research group decided to try representing children's knowledge as hierarchically arranged concepts and propositions, consistent with Ausubel's subsumption theory and based on evidence in the interviews. Thus was born a new knowledge representation tool Novak called the *concept map*. Figure 1 shows three concept maps prepared from interview transcripts for the same child after Grade 2, Grade 8, and Grade 12. The concept maps show expressly how Amy's knowledge of the particulate nature of matter developed over the span of the study.

The precision with which concept maps can represent changes in children's concept and propositional knowledge is illustrated in Amy's case. Amy received audio-tutorial lessons in grades one and two. We can see that at the end of Grade 2, Amy had acquired some understanding of the nature of molecules and some knowledge of the similarities and differences between solids (s) liquids (l) and gases (g). She mistakenly thinks air molecules are more "squeezable" than those of liquids or solids. It is common that children (and adults) confer qualities of macro properties to microstructures. Her knowledge improved after instruction in general science in junior high school, and biology and chemistry in high school. However, she has acquired a new misconception that evaporation causes friction. Clearly her knowledge of evaporation and friction is faulty. Further information can be found in Novak and Musonda (1991).

The graduate students working on Novak's audio-tutorial project were soon reporting that they found making concept maps was helping them learn subject matter in courses they were taking. These comments led Novak to develop a new course, "Learning How to Learn", a course that led some students to change their careers. Novak subsequently published a book based on experiences in this course (Novak & Gowin, 1984).

When computer power for desktop computers began to be sufficient to create concept-mapping software in the early 1980's, new opportunities for using concept mapping as a knowledge representation tool began to emerge. The Florida Institute for Human and Machine Cognition, with funding from NASA, US Navy, National Security Administration, and other public and private sources created CmapTools, software expressly designed to create concept maps consistent with Ausubelian psychology and constructivist epistemology. This software is available at no cost at: http://cmap.ihmc.us. CmapTools software is being used in all disciplines, in corporations, and various governmental agencies all over the world, including collaborative learning venues. Further discussion of the use and applications of concept mapping can be found in Cañas et al. (2004), Novak and Cañas (2008), Novak (2010) and Moon, et al. (2011).

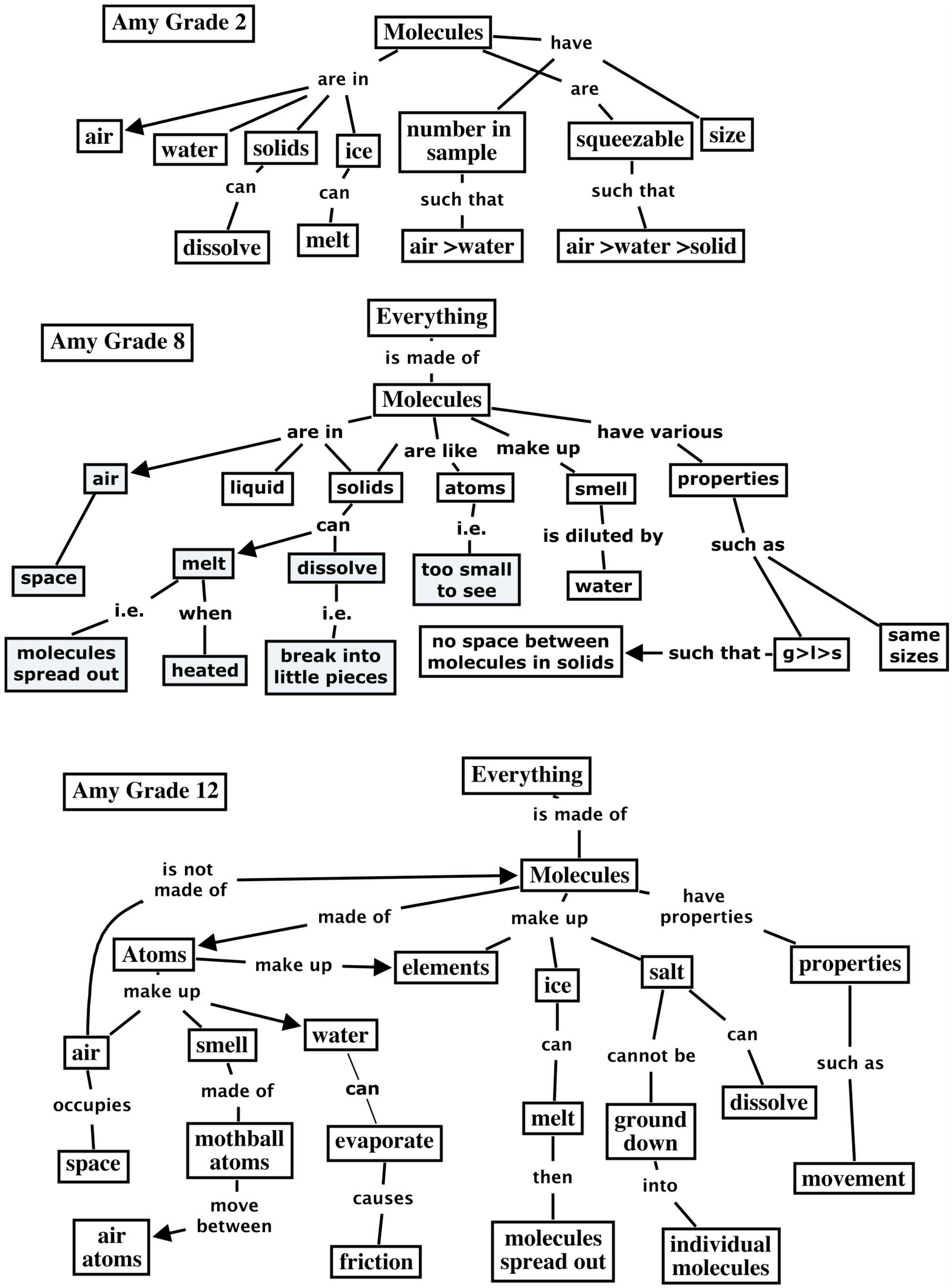

Figure 1. Concept maps drawn from interviews with Amy in grades 2, 8, and 12. Notice additions of concepts and some new, valid concepts and propositions, and some new misconceptions. From Novak & Musonda (1991).

Increasing evidence indicates the efficacy of using concept maps across the lifespan to improve information processing, and very likely in relation to dynamic brain functions correlated with the integrative processes of concept map construction. In an early study by Dunn and Novak in 1987, 6th grade children were successfully taught to make concept maps following the protocol in Novak and Gowin (1984). Subsequently these children were studied using EEG while they performed tasks using the concept maps they had created. First, one of the concepts was removed from the child's concept map projected on a screen and EEG recordings were obtained when the child was asked where on their map they would place the concept that had been removed. Second, the child was asked where they would place a new, relevant concept provided, and EEG patterns were recorded. Comparing EEG readings, highly statistically significant differences in the EEG patterns under the two different conditions were found. They interpreted the results to indicate that significantly different patterns of brain activity were found under the two conditions, with the addition of a new concept task obviously more cognitively demanding. Dunn's equipment did not permit more specific study of neural activity under the two conditions. We believe a similar study with modern more sensitive equipment and far greater computer power could provide some useful information on the relationships between cognitive functions during meaning making and activity patterns in brain regional activity. Since use of concept maps can provide very specific incidents of cognitive meaning making, they may help to interpret the role specific regions of the cerebral cortex play in meaning making. Unfortunately, Dunn died of cancer soon after this initial work, and papers on this work never were published, but it indicated a potentially productive line of research using more advanced neuroscientific technology.

ADVANCES IN NEUROBIOLOGY & ITS IMPLICATIONS FOR LEARNING STRATEGIES

With the emergence of cognitive theories in the mid twentieth century that focused on human information processing, dynamic encoding of information in memory and its recall for application in higher order thinking tasks (e.g., Ausubel, Bruner, Piaget), a new opportunity arose to explore how these mental representations could be explained by the expanding base of neuroscientific evidence on brain functions. Simultaneously, major advances were being made in more sophisticated methods of imaging and analyzing brain function, particularly higher brain centers in the cerebral cortex, including high resolution, multi-channel electroencephalographic analyses (EEG), and brain localization of activity by analysis of blood flow such as positron emission tomography (PET), using radioisotopic tracers, and functional magnetic resonance imaging (fMRI) (e.g., Dietrich & Kanso, 2010). Each of these modern techniques provides certain advantages depending on the goal of the research. EEG analyses, including event related potential analyses (ERP) that correlate brain activity with environmental stimuli, provide higher temporal resolution of brain electrophysiological responses due to the rapidity of recording brain electrical waves using advanced digital recording devices. fMRI and other brain imaging technologies permit a more detailed localization and interpretation of brain activity correlated with external environmental stimulation and information processing. However, because of the complexity of the instrumentation, there may be more constraints on mobility and capacity to interact with the environment compared to EEG analyses.

Application of Neuroscientific Research to Higher Cognitive Functions

With these more sophisticated tools, neuroscientists (who more typically had focused on biomedical applications) began to explore higher order functions of the human brain during "normal" information processing (e.g., Blakemore, 2000). These techniques improved localization of brain center activation and concurrently provided more precise temporal correlation with information input and human responding, yielding some significant insights about how different portions of the brain (modules) mediated normal brain functions. Among the important contributions to the synthesis of neuroscience with human cognition was the insightful work of Petri and Mishkin (1994) who demonstrated that higher functions such as conceptual representations and complex information processing of particular interest to cognitive theorists are mediated largely by higher cerebral centers; and classical conditioning through stimulus-response (S-R) connections, is largely mediated by lower, subcerebral centers. It is important to keep in mind, however, that all portions of the brain are interconnected by nerve fiber tracts, in some cases very massive tracts, that ensure coordinated whole brain functioning. Some major anatomical portions of the brain and their functions are presented in Figure 2.

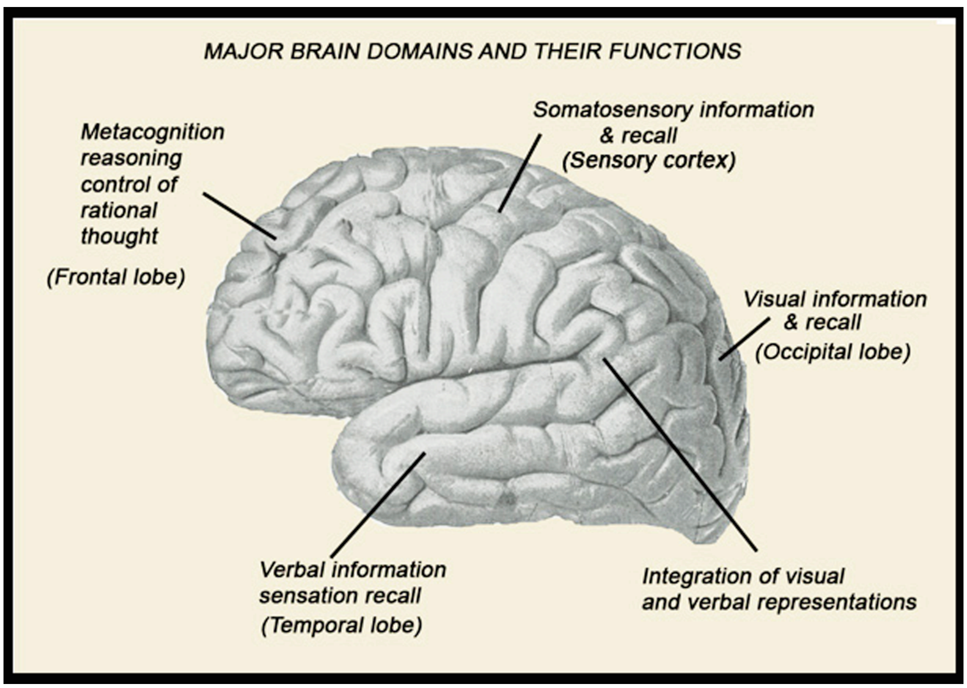

Figure 2. Brain anatomy and function: frontal lobe (executive functions and working memory), somatosensory cortex (body sensory information), parietal lobe (representation of spatial relations with environment), occipital lobe (visual sensation), and temporal lobe (language and auditory encoding).

At a more reductionist level, modern use of microelectrodes to record the functions of individual neurons or networks of neurons began to elucidate how connections are made among neurons in the brain during learning, and has largely supported Hebb's (1949) initial theories that synaptic connections between neurons are strengthened when the neurons are activated simultaneously (e.g., Kandel, 2001). Hebb, moreover, posited that mental representations and information in memory could be explained by "reverberating circuits of interconnected neurons" that were simultaneously activated during encoding of mental representations of experience. Current neuroscientific evidence also supports this general idea, namely higher order cognitive representations of experiences (such as categorical and conceptual knowledge), that are initially encoded in more fundamental, individual neuronal synaptic connections, become generalized at higher levels in the cerebral cortex by networks of activated multiple neurons that are linked to the lower order primary representation neurons. It is becoming increasingly clear that the brain is hierarchically organized at many levels from the cellular to the neuronal network level, with higher level assemblages of neurons modulating and, to some degree, regulating the activity of lower, more specialized neuronal centers (e.g., Anderson, 1991; Fodor & Pylyshyn, 1988; Tsien, 2007), and more recently in computer-based connectionist models of higher brain functions (Stern, 2013; Zatorre, 2013).

Emergence of Neuroscientific Applications to Learning and Remembering

As these neuroscientific insights were unfolding in the mid twentieth century, psychologists (e.g., Wittrock, 1992) began to take more interest in how the evolving evidence of cerebral functions could be used to explain more complex human behavior such as meaningful learning. Among some of the earliest applications in science education, Anderson (1983, 1991) summarized some of the current neuroscientific understandings of how the brain functions across major levels from the neuronal to the interconnected modular brain domains (anatomical regions), and mapped these into a fundamental model of how higher order information processing and meaningful learning could be explained by neuroscientific evidence. Subsequently, this was further generalized to include the neuroscientific correlates of cognitive learning theories that could help us better understand how complex learning is mediated by brain-based events (Anderson, 1997), including constructivist explanations of information processing and epistemology (Anderson, 1992, 2009a). Further explorations of the role of the frontal lobe in higher order conceptual reasoning and abstract learning, consistent with the models earlier proposed by Anderson, also began to appear in the latter decades of the twentieth century (e.g., Kwon, Lawson & Hur, 1997) including connectionist theories of science learning (Lawson, 2003, 2004).

However, some of the fundamental processes of how the brain coordinates working memory functions (partially mediated by frontal lobe and parietal lobes) with information input and output at a level of conceptual sophistication that typically occurs in classroom learning were not well developed. More recently a model representing the dynamic ways that working memory and sensory centers of the brain are coordinated to mediate knowledge formation and recall has been proposed by Anderson (2011) and placed within a larger exposition on current challenges of finding a middle-ground neuroeducational theory (Anderson, 2013). Fundamentally, this newer model of memory dynamic formation and recall, assumes that learning occurs in some generalized "context" through a process of assigning representative "labels" to categories of knowledge in memory. These labeled categories, moreover, become associated with "pointers" that represent general production rules indicating what other categories of knowledge can be connected to the referent labeled category based on prior learning. Each pointer moreover may have associated emotional valence (positive or negative) that influences the affective relationships among connected labeled items. Thus this model is designated as a "Context, Label, Pointer" model, abbreviated as CLP. For examples of its application and relevant diagrams, see Anderson (2011), a freely available online publication. In brief, the CLP model is intended to explain how the brain functions in working memory to dynamically generate networks of knowledge recall by mobilizing categories of knowledge within a given context, activate relevant pointers associated with those categories as pertinent to the context, and mediate the sequential linkage of these categories into an unfolding network of connected ideas. Thus, potential networks of knowledge are not assumed to be stored statically in the brain, but rather such networks are dynamically constructed by mobilizing categories of knowledge and utilizing prior learned pointers to link the knowledge categories into meaningful networks relevant to the particular context for the recall activity that is underway. Application of neuropsychological tests provides evidence that dynamic assembly of knowledge networks in memory is mediated by frontal lobe activity (e.g., Anderson 2009b). As some neuropsychologists state it, "recall that is constructed on the fly". This is also consistent with Ausubel's ideas of progressive differentiation and integrative reconciliation that mobilize thoughts and feelings from different brain regions both in knowledge acquisition and in use of information in complex problem solving or creative work.

In contrast to older models of a "Memory trace," that presumed there is some fixed stored source for knowledge in memory, the CLP model assumes that complex expressions of knowledge are assembled in working memory through purposeful arousal of categories of knowledge and dynamically linking them into propositional networks. This is accomplished through the systematic activation of previously learned pointers that coordinate the kinds of categories to be logically linked to one another as recall unfolds in time. Among the kinds of contexts that can be used to dynamically assemble these networks are content-based conceptual frameworks, logical hierarchical-subsumptive construction rules, logico-semantic rules such as hypothetico-deductive reasoning, and other generalized ways of mobilizing categories of information based on formal or informal prior learning experiences. Humans also can clearly apply reflective thought to generate new contexts through internal logical information processing, and thus to generate new sets of pointers to allow networking of information during recall in novel ways that may not have been learned previously. These forms of insight, and processes of meta-cognitive thinking, are among the more sophisticated ways that humans construct new contexts internally to create new sets of pointer-connected categories that can be dynamically assembled in novel networks of knowledge recall, beyond those gained through formal or informal prior learning.

NEUROSCIENTIFIC IMPLICATIONS FOR AUSUBELIAN THEORY & CONCEPT MAPPING

Some of these newer insights about the neuroscientific bases of human information processing are particularly consistent with Ausubel's theory of knowledge based on the role of prior knowledge, and its hierarchical subsumptive organization, for efficient encoding and recall. Moreover, substantial research, especially in science education, on the effective role of concept maps and other forms of mental cartography, derived from Ausubel's pioneering research as documented in the opening sections of this paper by Novak and colleagues, is also particularly supported by current neuroscientific-based theories of human cognition. We conclude by suggesting some of the ways modern neuroscientific research and neurocognitive theory, as summarized in the foregoing section, has contributed to strengthening the fundamental premises of Ausubelian theory and its application through concept maps. With respect to Ausubel's assumptions that new knowledge is subsumed within existing knowledge during meaningful learning, there is increasing neuroscientific evidence that new information is connected to earlier information within neural networks through extension of existing, related, neural centers of information storage. That is, new information in memory becomes incorporated within existing networks of information by synaptic linkages that extend existing related neural networks (e.g., Park & Friston, 2013; Tsien, 2007). Moreover, categories of information represented by these neural networks are likely organized in a hierarchical manner. In these neuronal models of the memory code, more specific categories of information are encoded in localized smaller neuronal networks that are connected by reciprocal nerve fibers to higher-level networks, encoding more generalized representations of the information. Interconnectivity and mechanisms for adjusting the strengths of the interconnections based on experience are essential attributes of these models. These findings suggest to us that there may a relationship between the hierarchically organized concepts and propositions represented in concept maps and the neurological organization manifest in neuroimaging studies of brain functioning. We propose that there may be value in conducting studies similar to that done by Dunn and Novak in 1987 (e.g., Dunn et al., 1989), but with the vastly greater resolution of modern neuroscientific techniques.

However, it is also known that information in memory is stored within the sensory cortex where it was perceived and encoded, at least initially: visual memories are stored in the occipital lobe at the back of the brain where visual imagery is first encoded. Linguistic information is stored in the temporal lobe where language is most typically encoded, etc. Organized recall of information is currently believed to occur in working memory, largely localized in the frontal lobe where executive functions are particularly specialized, and in conjunction with the parietal lobe. Working memory is dynamic and recruits information from the memory storage sites to assemble it into meaningful representations for recall. One of the most effective ways of doing this, consistent with the levels of organization in the knowledge storage sites, is to use a hierarchical organizing principle, consistent with Ausubel's original assumptions. However, as we know, human information processing is notable for being highly plastic and often divergent. The patently creative expression of human knowledge organization in recall is largely attributed to the dynamic information assembly potential of working memory. Among some of the most efficient ways of mobilizing and assembling information in working memory is in networks of connected ideas, as for example represented by concept maps and other mind mapping methods. Again, this form of organization most clearly mirrors the kind of information organization within neuronal assemblages – that is networks of interconnected neurons arranged in increasingly general inclusive assemblages (e.g., Markov et al., 2013). Current theories of how we actively assemble networks of information, such as the CLP model cited above (Anderson, 2011), fully support the dynamic way that individuals construct Ausubelian-based concept maps and other forms of mind mapping based on network theories. For example, using a hierarchical context as the guiding principle, information mobilized in working memory can be linked semantically by mobilizing appropriate pointers associated with each item of memory in the concept map. Each of these items is represented by a label, both in concept maps and in the CLP theory. The richer the set of pointers associated with any set of memory items to be connected, the more likely that a highly organized and richly interlinked map can be produced. Moreover, in the process of constructing such maps, additional pointers may be discovered and added to the existing set associated with the information items being constructed in the concept map. Therefore, a concept map is both a way of utilizing existing knowledge to assemble highly ordered networks, and in the process a potentially effective and creative way of discovering additional new ways of interconnecting information through the discovery of new categories and their interconnecting pointers.

SUGGESTIONS FOR APPLICATION OF MODERN NEUROSCIENTIFIC RESEARCH METHODS TO ANALYZE BRAIN PROCESSES DURING MIND MAPPING USING CONCEPT MAPS

With increasing advances in the enhancement of human information processing and meaningful learning in the disciplines, especially through innovations such as concept maps and associated mind mapping applications, additional opportunities to utilize modern neuroscientific techniques to analyze human learning during complex cognitive tasks become increasingly feasible. We present some suggestions for how neuroscientific experimentation can enhance our understanding of brain functions during complex information processing such as concept mapping; and, conversely, ways that complex tasks such as concept map activity may be a useful experimental venue to further characterize how the brain functions during normal information processing tasks.

Although it is clear from many educational research studies that concept maps can enhance learning and help students organize information more effectively, we do not fully understand the cognitive and neuroscientific bases. It is likely that making a concept map mobilizes a wide variety of brain functional domains, because it requires visual, semantic, memory (long-term and working) and psychomotor functions, among others. The particular neuroscientific correlates of concept mapping could be elucidated by combining ERP and fMRI analyses of individuals while they are producing concept maps in comparison to their production of other diagrammatic modes of representation. For example, brain analyses could be obtained while an individual reproduces a concept map that they have already learned how to make in comparison to brain analyses when they draw and label a diagram related to the same information. Further modifications may include comparing concept mapping with semantic tasks such as outlining and highlighting the information when mobilized from memory; each variation providing nuanced information on differences in brain function specifically related to concept mapping compared to the other information processing tasks. It also may be informative to examine brain functions when someone reconstructs a concept map from memory, versus extending the map by making new network connections. Because concept mapping is particularly based on cognitive paradigms for meaningful learning, it may be productive to examine differences in brain function when someone is learning information by rote as opposed to learning it as a network of ideas. Some evidence suggests that frontal lobe activity is particularly indicated when information is processed through networking of ideas (e.g., Anderson, 2009b). However, the evidence is based largely on inference from neuropsychological tests. Additional information on localization of brain activity by modern direct visualization techniques should provide a broader base of evidence. There appears to be large differences in individual's proclivity and skill in learning new verbal material meaningfully, as in concept mapping, rather than by rote (Novak & Gowin, 1984, Novak, 2010). These differences appear to operate in all domains of knowledge, and hence they may offer another avenue of research using modern brain visualization techniques. For example, with appropriate computer-based interactive interfaces, it should be possible to use ERP analyses of people learning information by rote associations, versus making concept maps, or other visual-semantic ways of representing information in memory. Brain visualization techniques combined with eye-tracking methods and recording of computer-based interactions, may help delineate the particular way concept mapping supports more meaningful and effective learning.

Much research has been devoted to analyzing the cognitive bases of information processing by experts versus novices within a field of knowledge (e.g., Chi et al., 1981). It may be informative to analyze differences in brain activity when a concept map is produced by an expert within a given domain of knowledge compared to a novice of similar age and prior educational experience. Also, one would expect that individuals who have organized information in memory using a concept map may be able better to mobilize and apply it; some interesting brain analysis experiments could be done comparing the problem solving processes of individuals who made concept maps during learning with those who did not. Because concept map construction provides a clearly defined and formal way of organizing information, including a hierarchical design and propositional mode of making linkages, appropriate to representation of meaningful learning in a wide range of disciplines and fields of endeavor, this medium may be a useful way of improving the analysis of brain function within carefully controlled circumstances. That is, in addition to educational insights about concept mapping that may accrue from applying modern brain analysis techniques, variations in the kind of information to be represented during concept mapping and the ways the information is subsequently applied may also provide deeper insights into how the “normal” human brain operates during tasks typical of daily information processing both in formal and informal settings. Increasingly, neuroscientific theories of human information processing during learning and empirical, research-based evidence of using concepts maps in education point to the value of concept maps in promoting a rich and lasting meaningful representation of generative knowledge in memory. Applying modern neuroscientific analysis techniques to further explore brain correlates of concept map construction during learning and recall may provide additional insights to refine concept map applications in education and concurrently expand our understandings of the neural bases of meaningful human learning. Concept maps might serve as a kind of “Rosetta Stone” to assist in the interpretation of neurobiological images taken as individual’s perform specific learning and recall tasks.

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REFERENCES

Anderson, O. R. (1983). A neuromathematical model of human information processing. *Journal of Research in Science Teaching*, *20*, 603-620.

Anderson, O. R. (1991). Neurocognitive models of information processing and knowledge acquisition. *Progress in Sensory Physiology*, *12*, 115-192.

Anderson, O. R. (1992). Some interrelationships between constructivist theories of education and neurocognitive theory with applications to science education. *Journal of Research in Science Teaching*, *29*, 1037-1058.

Anderson, O. R. (1997). A neurocognitive perspective on current learning theory and science instructional strategies. *Science Education*, *81*, 67-90.

Anderson, O. R. (2009a). Neurocognitive Theory and Constructivism in Science Education: A Review of Neurobiological, Cognitive and Cultural Perspectives. *Brunei International Journal of Mathematics and Science Education*, *1*, 1-32.

Anderson, O. R. (2009b). The role of knowledge network structures in learning scientific habits of mind: Higher order thinking and inquiry skills. In I. M. Saleh and M. S. Khine (Eds.) *Fostering Scientific Habits of Mind: Pedagogical Knowledge and Best Practices in Science Education.* Pp. 59-82.

Anderson, O. R. (2011). Mind, Brain and the Organization of Knowledge for Effective Recall and Application. *LEARNing Landscapes* (special issue on Brain, Mind and Learning), *5*, 45-61. [http://www.learninglandscapes.ca/images/documents/ll-no9-final-lr-links.pdf]

Anderson, O. R. (2013). Progress in application of the neurosciences: The challenge of finding a middle-ground neuroeducational theory. *International Journal of Science and Mathematics Education,* published online 13 Nov. 2013; link.springer.com/content/pdf/10.1007%2Fs10763-013-9455-3.pdf.

Ausubel, D. P. (1963). *The Psychology of Meaningful Verbal Learning*. New York: Grune and Stratton.

Ausubel, D. P. (1968). *Educational Psychology: A Cognitive View*. New York: Holt, Rinehart and Winston.

Ausubel, D. P., Novak, J. D., & Hanesian, H. (1978). *Educational Psychology: A Cognitive View* (2nd ed.). New York: Holt, Rinehart, and Winston.

Blakemore, C. (2000). Achievements and challenges of the Decade of the Brain. *EuroBrain*, 2, 1-4.

Cañas, A.J. Hill, G., Carff, R., Suri, N., Lott, J., Gómez, G., Eskridge, T., Arroyo, M., Carvajal, R. (2004). CmapTools: A Knowledge Modeling and Sharing Environment. In *Concept Maps: Theory, Methodology, Technology, Proceedings of the First International Conference on Concept Mapping*, Pamplona, Editorial Universidad Pública de Navarra.

Chi, M. T. H., Feltovich, P. J., & Glaser, R. (1981). Categorization and representation of physics problems by experts and novices. *Cognitive Science, 5*, 121-152.

Dietrich, A., & Kanso, R. (2010). A review of EEG, ERP, and neuroimaging studies of creativity and insight. *Psychological Bulletin*, *136*, 822-848.

Dunn, B. R., Novak, J. D., Hill, R., MacQueen, K., & Wagner, L. (1989). *The measurement of knowledge integration using EEG frequency analysis*. Paper presented at the 1989 annual meetings of the American Educational Research Association, San Francisco, California.

Fodor, J., & Pylyshyn, Z. W. (1988). 'Connectionism and cognitive architecture.' *Cognition*, *28*, 3-71.

Hebb, D. O. (1949). *The Organization of Behavior: A Neuropsychological Theory*. New York: Wiley.

Kandel, E. R. (2001). The molecular biology of memory storage: a dialogue between genes and synapses. *Science, 294*, 1030–1038.

Kwon, Y. J., Lawson, A. E., & Hur, M. (1997). The role of the prefrontal lobes in scientific reasoning. *Journal of the Korean Association for Research in Science Education*, *17*, 25-540.

Lawson, A. E. (2003). *The Neurological Basis of Learning, Development and Discovery: Implications for Teaching Science and Mathematics.* Dordrecht, The Netherlands: Kluwer Academic Publishers.

Lawson, A. E. (2004). Reasoning and brain function. In R. J. Sternberg & J. P. Leighton (Eds.), *The Nature of Reasoning.* New York: Cambridge University Press.

Markov, N. T., et al. (2013). Cortical high-density counterstream architectures. *Science, 342*, 1238406. DOI: 10.1126/science.1238406.

Moon, B. M., Hoffman, R. R., Novak, J. D., & Cañas, J. J. (2011). *Applied Concept mapping: Capturing, analyzing, and organizing knowledge*. New York: CRC Press.

Novak, J. D. (1977). *A Theory of Education*. Ithaca, NY: Cornell University Press.

Novak, J. D. (1993). Human constructivism: A unification of psychological and epistemological phenomena in meaning making. International Journal of Personal Construct Psychology 6:167-193

Novak, J. D. (2010). *Learning, Creating, and Using Knowledge: Concept maps as facilitative tools in schools and corporations*. New York: Taylor-Francis.

Novak, J. D., & Cañas, A. J. (2008). *The Theory Underlying Concept Maps and How to Construct and Use Them.* Technical Report IHMC CmapTools 2006-01 Rev 2008-01. Retrieved from: http://cmap.ihmc.us/docs/theory-of-concept-maps.

Novak, J. D., & Gowin, D. B. (1984). *Learning How to Learn*. New York: Cambridge University Press

Novak, J. D., & Musonda, D. (1991). A twelve-year longitudinal study of science concept learning. *American Educational Research Journal*, *28*(1), 117-153.

Park, H.-J., & Friston, K. (2013). Structural and functional brain networks: From connections to cognition. *Science* 342, 1238411. DOI: 10.1126/science.1238411.

Petri, H. L., & Mishkin, M. (1994). Behaviorism, cognitivism and the neuropsychology of memory. *American Scientist*, *82*, 30-37.

Stern, P. (2013). Connection, Connection, Connection.. *Science*, 342, *DOI:* 10.1126/science.342.6158.577

Turke-Browne, N. B. (2013). Functional Interactions as Big Data in the Human Brain. Science, 342, DOI: 10.1126/science.1238409.

Tsien, J. Z. (2007). The memory code. *Scientific American*, *297*, 52-59.

Wittrock, M. C. (1992). Generative learning and the brain. *Educational Psychologist, 27*, 531-541.

Zatorre, R. J. (2013). Predispositions and Plasticity in Music and Speech learning: Neural Correlates and Implications. *Science*, 342, DOI: 10.1126/science.1238414.