A Systems Approach to Science Education – Research Summary

(l'article de vulgarization)

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Theoretical Foundation and Rationale of the Study

The literature of schema-based learning theories describes three types of learning: accretion, tuning and cognitive restructuring (Rumelhart & Norman, 1976). Research conducted in the area of cognitive restructuring generally is assembled under the heading of *conceptual change*. The literature tells us that it is very difficult to achieve conceptual change and may account for difficulties reported in learning some important science concepts such as electricity in physics (Chi, Feltovich, & Glaser, 1981; White, 1993), gas laws and equilibrium in chemistry (Wilson, 1998), and in the biological sciences such concepts as diffusion, osmosis (Odom, 1995; Settlage, 1994), and evolution (Anderson & Bishop 1986; Brumby, 1984; Jacobson & Archodidou, 2000).

A traditional method used to facilitate conceptual change has been to provide the learner with examples that contradict their "naïve theories", this is referred to as *anomalous data* approach. However, such studies have produced unequivocal results (e.g., Limón, 2001). Chinn and Brewer (1993) propose that the crux of the problem is the learner's efforts to coordinate theory and data. These authors offer four characteristics that may account for the different responses to anomalous data: (1) entrenchment of prior theory; (2) ontological beliefs; (3) epistemological commitments; and, (4) background knowledge.

Chinn and Brewer (1993) also tell us that in the case of robust misconceptions, these four characteristics may not play an equal role. Intuitive “naïve” beliefs about the nature of existence and the fundamental categories and properties of the world (ontological beliefs), and beliefs about knowledge and how it is acquired (epistemological beliefs), may be deeply intertwined with who we are, as well as how and what we can learn. Chi, Slotta, and deLeeuw (1994), Strike and Posner, (1992), and Vosniadou (1994) support this point-of-view and categorize the problem of robust misconceptions as stemming from these fundamental beliefs or "theories" held about the properties of the concept.

Purpose of the Study

This study took as its starting point the conceptual change theory proposed by Chi and her colleagues (Chi et al., 1994; Ferrari & Chi, 1998; Slotta & Chi, 1999). The basic assumption of their theory is that all conceptions are classified into ontological categories — ordered hierarchical trees of super-ordinate and subordinate systems — based on attributes that are perceived or suggested to the learner. These schema-like associations act as facilitators or inhibitors of future transfer of knowledge and are part of general accretion and tuning. One approach to overcoming such limiting habits may involve the reassignment of concepts from the “clockwork” explanation of causality (often held by novice learners) to a scientifically correct “emergent” causal explanation (Chi et al, 1994; Chi & Roscoe, 2002). We wished to explore this theoretical position of achieving conceptual change and improving the understanding of particular science concepts (i.e., evolution) by providing the learner with the alternative emergent causal explanatory framework.

If we were to accept this approach to conceptual change, then we needed to address the question of: how do we provide learners with an awareness of *emergence*[1] and emergent causation? The literature related to teaching about “complex systems” provided one possible answer. “*In the minds of many, the study of complexity is not just a new science, but a new way*

[1] *Emergence*, is defined as: a phenomenon which relies on the interactions of multiple agents, all operating under the same constraints (rules) without centralized control, yet affected by probabilistic causes and feedback loops that generate nonlinear effects creating dynamic self-organizing systems behaviors.

of thinking about all science, a fundamental shift from the paradigms that have dominated scientific thinking for the past 300 years" (Resnick & Wilensky, 1997, p. 4). Initial studies conducted by Resnick (1994) and Wilensky (1995) tell us that the use of particular types of simulations can offer an understanding of specific aspects of complexity – knowledge of the process of emergence and the subsequent development of non-isomorphic levels of organization. They have demonstrated that the use of StarLogo™ simulations is a powerful means of facilitating the acquisition of knowledge about complex systems, and accompanying emergent processes. However, other literature on complex systems thinking also reveals that students have great difficulties acquiring this understanding of "emergent causal processes" (e.g., Duit, 1998; Jacobson, 2000; Penner, 2000). Therefore we also explored the potential of these simulations to provide support (often referred to as "affordances") for acquiring an emergent causal explanatory framework. Specifically, we examined which aspects of the five identified components of complex systems thinking (i.e., non-isomorphic multiple levels of organization, decentralized control, randomness, nonlinearity, probabilistic behavior, and dynamic homeostatic behaviors) were most difficult for the learners to acquire.

Lastly, this study reflects on the appropriateness and "learnability" of the topic of complex systems for students at this educational level. For instances, Boyd (1997) suggests that it is possible to introduce elements of "cybersystemics" (i.e., elements of complex systems thinking) into the regular curriculum. Others such as Auyang (1997), Bar-Yam (1997), Kaput, Bar-Yam, and Jacobson (1999) contend that complex systems may function as a unifying and cross-disciplinary theme. In the most recent *New England Complex Systems Institute annual conference*, Jacobson, Jakobsson, Lemke, and Wilensky (2002) challenged the science education community to explore the potential of using complex systems ideas in the classroom. They stated: "the conceptual basis of complex systems ideas reflects a change in perspective about our world that is important for students to develop, as it corresponds to the scientific environment that will exist when they graduate. This perspective emphasizes both the limits of predictability as well as the possibility of understanding indirect consequences of actions taken, both positive and negative, through modeling the interdependence of our world" (p.2). Therefore we provide some insights into this possibility.

Research Questions and Methods

1. Do student's explanatory frameworks of scientific phenomena (ontological beliefs) change as a consequence of an instructional intervention utilizing simulations of complex systems (i.e., StarLogo) and supported by cognitive scaffolding?
2. What Complex Systems concepts do students acquire during the instructional activities?
3. What is the development of students' systems thinking?

The study was a mixed method qualitative case study design which engaged the theoretical sampling strategy of "purposeful" sampling (Creswell 2002) to select nine cases. Hence, the participants were selected basis on their ability to help the researchers understand this learning process (all first year Cegep science students).

The experimental intervention consisted of five one-hour sessions that involved the use of different StarLogo simulations: Slime, FreeGas, Wolf-Sheep. Over this period the nine students, met individually with the coach and worked with the simulations. Metacognitive prompts were provided as needed.

Data were collected from direct observations (audio and video tapes of the instructional activities), written documents (students' responses at the pretest and posttest, and concept maps), and interviews. This data was subsequently used to construct two measures, a measure of the students' explanatory frameworks – Ontological Beliefs measured by (EFMM) – and a measure of the students' Conceptual Understanding of Complex Systems (CST).

Findings of the Study

The findings were as follows: (1) Although students experienced gains in the of the five component features of emergent causal processes, their difficulty with the concepts of "random actions" of agents and "nonlinear effects" of agents constrained their deeper understanding of emergent causal processes. (2) Although the StarLogo simulations facilitated the acquisition of certain aspects of this knowledge, it provided no affordance for learning the concept of "nonlinearity". Furthermore, aspects of these multi-agents representations generated conflicting ontological explanations for the concept of "randomness". (3) Although the selected StarLogoT simulations demonstrated emergent causal processes, they represented different types of complex systems (i.e., tightly coupled and dissipative loosely coupled). Although most students had difficulty with the representations of dissipative systems, those who had a more advanced understanding of science concepts gained an understanding of emergent causal processes from dissipative representations. (4) Conceptual change required metacognitive scaffolding and ongoing metaconceptual prompts during the instructional phase. However, once students acquired *synthetic mental models*[2], maturation over time and experience with complementary domain curricula was sufficient for them to elaborate their understanding of emergent causal processes.

Educational Implications

Three main educational implications can be drawn from this study: (1) students exhibited ease in acquiring certain components of emergent framework mental models even with a short-term intervention. Therefore this learning goal may be achievable without major additions to the curriculum; (2) there is need for a greater understanding of emergent causal processes by curriculum developers (e.g., instructional designers) and teachers (e.g., professional development and teacher training programs) so that they are more aware of the many opportunities to apply this knowledge. Additionally, until recently there has been a lack of representational tools to readily convey emergent processes as demonstrated by complex systems and thereby provide the necessary scaffolding for learning these concepts. While these tools are making their way into the educational system, there is a need to develop the easily accessible curricula topics that demonstrate complex systems behaviors (e.g., respiration, and cardiovascular circulation in the health sciences, the behavior of geological and ecological systems in the natural sciences); (3) this alternative explanatory framework may be beneficial for all disciplines not just science. If students are better able to explain the social, political, and economic interactions they encounter

[2] According to Vosniadou and colleagues (e.g., Vosniadou & Brewer, 1994; Vosniadou et al., 2001) synthetic models are formed in the problem-solving context as learners attempt to reconcile the "new" view with the existing underlying ontological and epistemological presuppositions, which are referred to as "component beliefs" (in Jacobson & Archodidou, 2000).

with more than a linear perspective they may in fact do a better job of understanding the unpredictable, and probabilistic nature of many of these phenomena.

Conclusion

In conclusion, the results of this study provide strong support that the ontological training facilitated the creation of emergent framework mental models (EFMMs). The evidence that most students acquired at least three of the Complex-Systems concepts supports this conclusion

The affordances for learning aspects of emergent causal processes offered by the multi-agent models/simulations are highly related to the type of complex system represented and also to the students' background understanding of science. In particular more students had difficulty learning with representations (simulations) of dissipative system complexity compared to those using representations of tightly coupled organization models of complexity.

Conceptual change requires not only robust conceptual representations (e.g., models that can be used as analogies) but also metacognitive scaffolding and ongoing metaconceptual prompts during the instructional phase. Once initiated (i.e., once synthetic mental models are created), maturation over time and experience with complementary domain curricula appear to have positive effects on the development of more elaborated emergent framework mental models.

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