Abstract

It is generally accepted that the cognitive development for a wide range of students can be improved through adaptive instruction - learning environments optimized to suit individual needs (e.g., Cronbach, 1957; Lee & Park, 2007; Shute & Zapata-Rivera, 2007). It is vital in adaptive instruction to diagnose an individual's learning progress in terms of cognitive changes in complex problem-solving contexts. This study conceptualized the levels of learning progress, associating the development of expertise in domain learning with the structural features of mental models. The theory of mental models accounts for how people conceptualize problem situations. That is, a mentally represented problem space is a structure including diverse relationships. It is necessary that assessment tools be adapted for the complex, dynamic structure of mental models so that the diagnostic, formative information become more precise. In short, the proposed stage-sequential model of learning progress was theoretically justified as being able to serve as a diagnostic model of learning progress.

*Keywords*: learning progress, mental models, cognitive change, problem solving

# Theoretically Grounded Guidelines for Assessing Learning Progress: Cognitive Changes in Ill-Structured Complex Problem-Solving Contexts

Spector (2004) framed a central question pursued in the field of instructional technology as “how to assess progress of learning in a complex domain.” (p. 276). Learning progress can be defined as the changes in a learner’s understanding, which are gradually modified through instruction in the direction of expert-like knowledge and performance (Ifenthaler & Seel, 2005; Schlomske & Pirnay-Dummer, 2008; Schvaneveldt, Durso, Goldsmith, Breen, & Cooke, 1985; Seel & Dinter, 1995; Snow, 1990).

Ill-structured complex problems (such as those that occur in domains such as engineering design, environmental planning, etc.) are characterized by their unknown elements, lack of a clear path to solution, and multiple (or lack of) solutions (Jonassen, 2000; Pretz, Naples, & Sternberg, 2003; Spector, 2008b, 2008c; Wood, 1983). The purpose of this paper is to develop a theoretically grounded framework to guide and advance the assessment of learning progress in ill-structured complex problem solving situations. The discussion centers on theories and models applicable to formative assessment in terms of recognition of the relevance of internal representations in the development of knowledge and expertise and the features of a knowledge base that indicate levels of problem solving.

In an instructional situation, one may experience three challenges when assessing and monitoring learning progress and promoting improvements in problem solving. First, it is difficult in a complex problem-solving situation to establish standards or reference models as targeted expert models against which students’ levels of understanding are identified and monitored. Instruction that aims to develop a student’s expertise in problem-solving situations probably begins with the assessment of the student’s level of understanding and the identification of areas for improvement (van Gog, Ericsson, Rikers, & Paas, 2005). Accordingly, a method for eliciting a learner’s problem conceptualization is required (Ericsson & Simon, 1980, 1993; Pirnay-Dummer, Ifenthaler, & Spector, 2010; Schvaneveldt et al., 1985; Schvaneveldt, 1990; Spector & Koszalka, 2004; Taricani & Clariana, 2006), and determination of a learner's progress necessitates having a reference model (Carver, 2006; Ifenthaler & Seel, 2005; Schlomske & Pirnay-Dummer, 2008; Spector, 2008a).

Second, a theoretically sound and systematic assessment model likely composed of qualitatively distinct stages is desired. This study assumes that students experience changes in their understanding in response to solving problems. The development of mental models can be characterized as progressing through qualitatively different mental stages, from a lower level toward an expert-like level. For example, a young student who used to believe the earth is flat can experience a conceptual shift and begin to see that the earth is spherical. An assessment model provides a theoretical framework to determine levels of expertise, explain learning progress, and provide adaptive instruction that meets individual requirements in terms of differences in stages of expertise and established problem space.

Third, it is important to see the learner's progress in a longitudinal manner so that one can evaluate the effects of an instructional intervention. Two issues of monitoring learning progress are discussed, providing that learning progress is the change in qualitatively different levels of understanding: (a) it is anticipated that there is often a reversion to an earlier or less sophisticated stage of learning progress when confronted with a particularly challenging problem; and (b) it is important to determine whether learners achieve particular levels of problem-solving knowledge and skills and are able to adapt their knowledge and problem-solving skills to new situations.

Drawing on the theory of mental models, developmental psychology, and studies of expertise development, this study develops testable propositions that are applicable to the effective design of formative assessment.

## Assessment of Learner Understanding

### Re-represented Mental Models as Learner Models

The theory of mental models describes both knowing and teaching in terms of how knowledge is represented in the human mind, how learning evolves and how learning progress is conceptualized in the context of instruction. Mental models are defined as iconic cognitive artifacts presumably constructed by an individual based on his/her preconceptions, cognitive skills (e.g., critical thinking, meta-cognitive skills), linguistic comprehension, and perception of the problem itself (Anzai & Yokoyama, 1984; Craik, 1943; Greeno, 1989; Johnson-Laird, 2005a, 2005b; Kieras & Bovair, 1984; Mayer, 1989; Norman, 1983; Seel, 2003, 2004).

The cognitive artifacts evolve and are gradually modified through experience and instruction (Carley & Palmquist, 1992; Collins & Gentner, 1987; Seel, 2001, 2003, 2004; Seel & Dinter, 1995; Shute & Zapata-Rivera, 2007; Smith, diSessa, & Roschelle, 1993). The theory of mental models provides a comprehensive perspective on knowledge building that includes both domain-general processes (i.e., those that transcend and contribute to cognitive development across domains; Kail, 2004; Sternberg, 2008) and domain-specific knowledge (Chi, Glaser, & Farr, 1988; Vosniadou, Vamvakoussi, & Skopeliti, 2008). Fundamentally, mental models are considered to be domain-specific in that they mirror the structure of what they represent (Johnson-Laird, 2005b; Seel, 2001; Spector, 2008a). However, the process of model building is largely influenced by domain-general processes such as meta-cognition, self-regulation, and cognitive flexibility (Collins & Gentner, 1987; Kail, 2004; Sternberg, 2008). According to cognitive psychologists, problem solving involves finding a reasonable course of action, often by making use of mental models (Johnson-Laird, 2005a; Norman, 1983; Seel, 2001, 2004) is accompanied or led by meta-cognition (e.g., reflection). For example, a law school student reading the testimony of an eyewitness in a criminal case might first construct an internal representation of the situation and then test that representation against other facts and testimony. The internal representations are typically quite specific to the situation. Afterwards, the student may reflect on the situation and reasoning about that testimony, deliberate on the implications and assumptions and possible alternatives, and then modify the representation to explain to him/ herself what probably happened. The interim deliberative process involves meta-cognitive processes that may lead to another domain-specific internal representation.

Second, the theory of mental models explains the process of building expertise. The process of building expertise can be explained as a way of constructing mental models. According to Piaget (1964), there are two different cognitive processes involved in mental model development − assimilation and accommodation. When encountering a new situation, a learner activates existing models analogous to the situation. By comparing the new information with the model, the new situation can be perceived in terms of the existing structure (Norman, Gentner, & Stevens, 1976; Rumelhart & Norman, 1978). Accommodation involves the modification of an entire model to fit a new experience when a learner fails to adjust (Gentner & Stevens, 1983; Johnson-Laird, 1983; Ifenthaler, 2010; Norman, 1983; Seel, 2003; Seel & Dinter, 1995).

One way to promote cognitive change is to provide appropriate cognitive conflict. This approach is grounded in a few well-known learning theories such as Piaget's (1976) process of equilibration, Festinger's (1962) notion of cognitive dissonance, and Vygotsky's (1934/1978) zone of proximal development. Vygotsky (1934/1978) said that "the only good learning is that which is in advance of development" (p. 82).

Third, the theory of mental models provides a measurable feature of existing knowledge. At first it might appear that mental models could not be the foundation for any kind of instructional planning or implementation since they are permanently hidden from view. That is to say that one cannot see a mental model directly. However, it is possible to elicit representations of these internal constructions and use them as the basis of judging how an individual's ability to reason about complex problems is developing (Axelrod, 1976; Cañas, 2009; Clariana & Wallace, 2007; Jonassen, Beissner, & Yacci, 1993; Spector & Koszalka, 2004). Mental model representations are believed to consist of propositional representations as structured symbols and images as visualized icons (Johnson-Laird, 2005b; Newell, 1990). According to this theoretical perspective, detecting those latent structures and changes as they evolve is a way to assess the development of complex problem solving skills. Learning progress is likely to be well-illustrated by the notion of mental models when learning progress is characterized as a set of directional changes in a learner's mental representations to a complex problem situation.

**Measurable Features of Mental Models as Structural Knowledge**

Problem solving often relies on a structural knowledge base that requires the integration of ideas and concepts (Dochy, Segers, Van den Bossche, & Gijbels, 2003; Jonassen et al., 1993; Segars, 1997). In that sense, assessment of problem solving necessarily takes into account the organization of the knowledge base, which requires a theoretical framework of knowledge structures involved in problem solving so that different levels of problem solving can be illustrated (Gijbel, Dochy, Van den Bossche, & Segers, 2005).

Spector and Koszalka (2004) first introduced three features (3S) of knowledge structures that likely describe mental models: (a) surface, (b) structure, and (c) semantic features (see Table 1). Those features have been used as a framework to develop assessment measures for mental models (Ifenthaler, 2006; Pirnary-Dummer, 2006). The 3S feature of knowledge structure was confirmed in this study as supported by studies in related areas such as elements of knowledge structure, analogy study, and linguistic comprehension. First, the surface feature indicates the descriptive information of components of a knowledge structure.

According to Sugrue's (1995) elements of a knowledge structure targeted by the assessment of problem solving, the surface feature relates to an understanding of concepts that are defined as "a category of objects, events, people, symbols or ideas that share common defining attributes or properties and are identified by the same name" (Sugrue, 1995, p. 9). Likewise, cognitive scientists account for the surface level of mental models as salient objects and aspects of the context (Holyoak & Koh, 1987; Simon & Hayes, 1976), and linguists studying linguistic comprehension describe the surface structure of linguistic representations characterize the shape of the sentences in terms of concepts and their relations in text (Katz & Postal, 1964).

Table 1

*Constructs Related to the Knowledge Structure*

| Features of Knowledge Structure (3S) (Ifenthaler, 2006, 2010; Pirnay-Dummer, 2006; Spector & Koszalka, 2004) | Elements of Knowledge Structure (Sugrue, 1995) | Analogy Study (Gentner & Medina, 1998; Holyoak & Koh, 1987; Judd, 1908; Simon & Hayes, 1976) | Linguistic Comprehension (Bransford & Franks, 1971; Bransford, Barclay, & Franks, 1972; Bransford & Johnson, 1972; Katz & Postal, 1964; Kintsch & van Dijk, 1978) |
|---|---|---|---|
| Surface feature | Concepts | Surface | Surface structure |
| Structural feature | Links from concepts and principles to conditions and procedures for application | Deep | Deep structure |
| Semantic feature | Principles | | |

The second indicator of a knowledge structure is a structural feature that describes the levels of size, complexity, and cohesiveness of mental models as a whole. Borrowing Sugrue's (1995) account, in this feature, concepts and principles are situated in particular conditions and procedures for application. At this stage, the focus of assessment of problem solving is on the “extent to which the student’s knowledge structure is organized around key concepts and principles that are linked to conditions and procedures for application” (Gijbels et al., p. 35). That is, the structural feature indicates a deep level in terms of a well-organized knowledge structure within a particular context in which underlying causal principles, including key variables and their relations, are subsumed (Gentner & Medina, 1998; Judd, 1908).

As the third indicator, the semantic feature shows the levels of understanding of concepts and their relations in a knowledge structure including principles that can be “a rule, law, formula, or if-then statement that characterizes the relationship between two or more concepts” (p. 9). Katz and Postal (1964) claimed that a substantial part of the meaning emerges from the semantic information of the deep structure. This idea is supported by studies of linguistic comprehension arguing that meaning stems from information integrated from the whole corpus (Bransford & Franks, 1971; Bransford, Barclay, & Franks, 1972; Bransford & Johnson, 1972; Kintsch & van Dijk, 1978).

Drawing on measures associated with three features (3S), researchers have investigated longitudinal changes in students’ mental models (Ifenthaler, Masduki, & Seel, 2009; Ifenthaler & Seel, 2005; Schlomske & Pirnay-Dummer, 2008). Key questions requiring further investigation emerged from those studies. For example, Scholmske and Pirnay-Dummer (2008) tracked changes of individual measures, so there was no comprehensive account of the learning status incorporating the multiple features of mental models. As an advanced approach, Ifenthaler and colleagues (2009) investigated longitudinal changes using Hierarchical Linear Modeling (HLM) techniques. Although that study involved multiple variables in different features, there were still critical limitations. First, multivariate HLM methods are on the whole based on the linear growth assumption. The descriptive statistics in their study demonstrated that there were diverse non-linear patterns in time according to the measures. These non-linear patterns imply that technical improvements in their HLM models or new interpretations of the features of knowledge structure are needed. Indeed, many of their measures had no significant relation to the learning outcome involving surface and structural measures. Second, they used an aggregated mean score to investigate overall trends. Mean scores possibly distort actual growth trajectories of the measures. Diverse patterns of mean scores of measures indicate that there was probably a greater variety of growth trajectories in each measure of an individual participant. Consequently, current approaches are limited to the use of diagnosing an individual's status of learning both in occasion and time.

This study questions the assumption used in the aforementioned studies that learning progress changes in a linear pattern, including the measures of knowledge structure. Instead, this study argues that the three features of knowledge structure have diverse patterns depending on the levels of learning, and the dynamics of these three features can define the qualitatively distinct stages of learning progress or transitions amongst stages.

**Problems in Building Reference Models of Complex Problems**

Problem solving is a goal-directed cognitive effort and requires an appropriate and adequate understanding of the problem (Anderson, 1980). Diagnosis of the levels of problem-solving knowledge and skills involves a comparison between mental models representing a problem-solver's existing understanding in the form of learner models and that of a targeted expert as a reference model. Both problem-solving and learning require reference models to identify, monitor and promote levels of expertise in problem-solving situations. Especially for instructional contexts, reference models may denote instructional goals, which have the critical functions of assessing the individual learning status and providing adaptive feedback in problem-solving tasks.

A possible argument against the need for a reference model is that people create their own understanding; this position is called radical constructivism. Another rebuttal would be that it is not plausible or reasonable to build reference models in complex and ill-structured problem situations because even experts' models will vary depending on their experiences. However, radical constructivism has no pragmatic utility in designing and implementing instruction and learning support, and is epistemologically flawed as it leads to the absurd conclusion that the only knowledge that exists is one's own. Moreover, methods to establish proper reference models to facilitate learners' problem-solving have proved to be useful in many situations. Again, it is notable that goal-directedness is a common trait of problem-solving, learning, and instruction. Theoretical discussions of problem-solving can provide a few plausible or pragmatic ways to reconcile the need for reference models with the impossibility of building references in complex and ill-structured problem situations.

Pretz and colleagues (2003) defined problem solving as a set of mental activities composed of (a) recognizing the problem, (b) defining and representing the problem, (c) developing a solution strategy, (d) organizing one's knowledge about the problem, (e) allocating mental resources for solving the problem, (f) monitoring one's progress toward the goal, and (h) evaluating the solution. These problem-solving processes can be dichotomized into two phases: planning (which includes (a) and (b)) and development (which consists of (c) through (h)).

Based on this theoretical background, it does seem possible to build reference models at least in the planning phase of problem solving. While solutions to ill-structured complex problems may be multiple and may be constructed through diverse paths, the planning phase can be somewhat invariant. The planning phase of problem solving is believed to end with the problem representation, which refers to "the manner in which the information known about a problem is mentally organized" (Pretz et al., 2003, p. 6). Newell and Simon (1972) claimed that a problem solver conceptualizes the problem space in which all of the possible conditions of a problem exist. Studies of expertise demonstrate a clear distinction among mentally represented problem spaces between experts and novices (e.g., Chi, Glaser, & Farr, 1988; Spector & Koszalka, 2004). Spector (2008a) argued that "experts would exhibit clearly recognizable patterns in their problem conceptualization, although experts did develop a variety of problem responses" (p. 31). That is, although levels of problem representations vary depending on an individual's level of expertise, experts in the same discipline typically have a relatively similar understanding of the problem space.

## Stage-Sequential Learning Progress

### Insights from Developmental Psychology

Behavioral learning theorists believe that human understanding grows continuously, without qualitatively distinct cognitive stages (e.g., Kendler & Kendler, 1962). In contrast, Piaget (1964) believed that children experience qualitatively distinct, sequential knowledge states (e.g., sensorimotor, preoperational, concrete operational and formal operational) while growing up. Although his notion of qualitative changes in a child's thinking has continued in contemporary developmental theories (Flavell & Miller, 1998), there are several departures from Piaget's conventional notion of developmental stages.

First, cognitive development of a child is probably more learning-dependent and less age-dependent than Piaget's early studies suggest. Piaget's (1964) main claim was that a child's development is an age-dependent progress. He suggested that a child of a young age is not likely to perform tasks requiring a higher level cognitive structure because his/her cognitive ability is still immature (Siegler & Klarh, 1982). In contrast, Bruner (1961) agreed with the qualitative stages of cognitive development but not with the age-dependent progress. Findings in developmental studies support Bruner's points. For example, many observations have discovered that some infants show precocious abilities (Flavell, 1992). In addition, unless adults have adequate and appropriate education or training, they may not be able to resolve Piaget's formal operational tasks (Shaklee, 1979).

Second, cognitive development is promoted by interactions between domain-general and domain-specific processes. There has been a longstanding debate whether development proceeds through a fixed sequence of stages across learning domains or through a specific fractionated manner within a particular subject area (Carlson, 2002; Case, 1992; Fischer & Silvern, 1985; Flavell, 1985). Piaget's (1964) theory postulates static, invariant developmental stages, which are domain-independent. Contrarily, contemporary studies suggest that the development of the human mind is neither explained by totally general, domain-independent stages nor only by domain-specific, fractionated knowledge (Flavell, 1992; Sternberg, 2008). Accordingly, it is important to note that a general stage-like development can still account for changes in understanding. In contrast, domain-specific knowledge appears to be more critical to building expertise.

Third, both learning and development proceed through similar qualitative changes. Piaget (1964) believed that learning and development are fundamentally dissimilar. Stage-sequential qualitative stages only occur in development (long-term change). Learning is viewed as short-term changes aimed at obtaining and accumulating domain-specific content knowledge (Siegler, 2005; Siegler, Thompson, & Opfer, 2009). In contrast, Werner (1957) and Vygotsky (1934/ 1978) believed that both learning and development basically evolve as the learner constructs qualitatively distinct knowledge structures. According to Siegler (2005), although some findings still seem to be related to the age-dependent changes asserted by Piaget, more findings indicate that children, even in a short-term period of learning, experience qualitative changes in mental model states (e.g., Chen & Siegler, 2000; Opfer & Siegler, 2004; Siegler et al., 2009). It is notable that children proceed through a similar progression of qualitatively distinct stages in both the short and long term, which may occur based on quantitative changes in the frequency of existing approaches (Siegler et al., 2009; Vosniadou et al., 2008).

**Stages When Expertise Develops**

This study argues that plausible stages applicable to the learning progress can be adopted from the studies of the development of expertise. Ericsson (2003, 2005, 2006) suggested that expertise is developed by a deliberate practice in which learners engage in appropriate and challenging tasks carefully selected by masters, devote years of practice to improving their performance, and refine their cognitive mechanisms by self-monitoring efforts such as planning, reflection, and evaluation. In this view, moving toward higher levels of expertise involves “changes to different knowledge structures and complex acquired mechanisms” (Ericsson, 2003, p. 67). The notion of deliberate practice implies qualitatively different changes in mental models, although Ericsson does not generate a model in which the developmental stages of expertise explicitly exist.

Considering the earlier discussion that people experience qualitatively distinct cognitive changes in the short- as well as long-term, changes of expertise development are likely to be applicable to describing the stages of learning progress. Current expertise studies tend to be interested in gaining expertise in domain specific learning and instruction (e.g., Alexander, 2003, 2004; Chi, 2006). For example, Chi (2006) developed a proficiency scale of expertise development, which was adapted from Hoffman (1998). She believed that the ultimate goal of studying for relative expertise is to enable less-skilled novices to become more knowledgeable by providing adaptive instruction based on their levels of understanding. Alexander (2003, 2004) introduced an account of multiple stages of expertise development focusing on the nature of developing expertise in academic domains.

**A Framework of Stage-Sequential Learning Progress**

Based on the aforementioned theoretical review of mental models, expertise development, and developmental psychology, a model of stage-sequential learning progress as a potential framework of learning progress is presented next (see Table 2). This model draws on the five stages of expertise development (Dreyfus et al., 1986) and three types of knowledge features−that is, in terms of surface, structure, and semantic feature−(see Table 1) associating the two approaches according to the notion that knowledge appears to be a configuration of mental representations as a whole.

Table 2

*A Framework of Qualitatively Distinct Stages of Learning Progress*

| Stage | Description |
|---|---|
| Novice (Irrelevant structure) | A beginner starts to learn context-free abstract knowledge and face situations in a new domain; concepts and relations are low in quantity compared to the reference model. |
| Advanced beginner (Surface structure) | A learner recognizes situational knowledge as well as non-situational knowledge but shows a lack of sense of what is important in a particular situation |
| Competent Learner (Deep structure) | With increasing experience, a learner chooses a perspective and then determines which elements of a situation are critical; most key concepts are posed in a learner's mental model, but the propositional relations among concepts are somewhat different from the reference model. |
| Proficient Learner (Semantically deep structure) | A learner approaches a problem holistically and immediately recognizes problem space; the expected concepts and relations among them are represented in a learner's mental model including situational and non-situational concepts. |
| Intuitive Expert (Advanced semantic structure) | An expert intuitively makes a decision about what the problem is and how it is resolved. An expert has tacit knowledge based on a vast number of relevant experiences. |

Although the scale proposed by Dreyfus and Dreyfus (1986) anticipates many other models, the scale appears to be more informative in accounting for the qualitative features of mental models at each stage and the progress of problem-solving skills. The five levels of expertise are used to denote a learner's stages of learning progress in a problem-solving situation. Associating the features of knowledge structure and the development of expertise characterizes each stage of learning progress learners' mental models fall into on a given occasion. A series of changes in the stages show a learner's learning trajectory, or learning progress. Figure 1 illustrates how an individual's mental models might progress through a sequence of different stages.

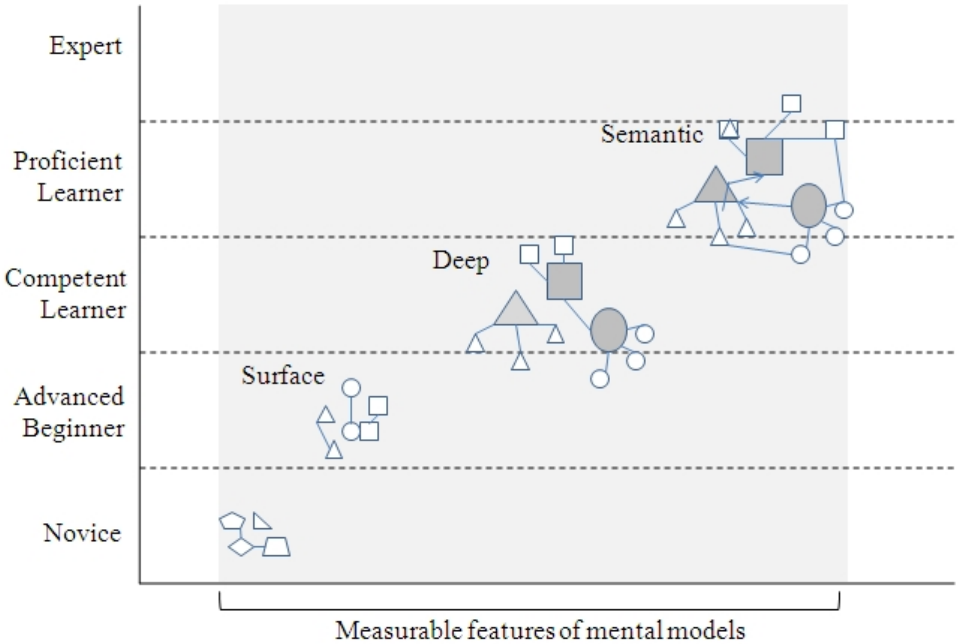


*Figure 1*. The stages of learning progress.

**Novice learner (Irrelevant structure)**. Novices are new to the domain and it is difficult for them to link their prior-knowledge to the new domain, thus rendering them as yet unable to represent new knowledge. This level represents a stage at which learners lack knowledge at both the contextual and principle levels resulting in a poor representation of their thoughts and ideas. Two types of mental models are assumed at this stage: (a) all features (surface, structure, and semantic) of novices' knowledge structures are quite dissimilar to those of experts; or (b) the structure feature could be seen to be mastered because mental models consisting of a small number of concepts and relations are likely to look cohesive and connected. That is in accord with the claim that a structural graphical approach is insufficient for interpreting mental models (Forbus, Gentner, Markman, & Ferguson, 1998; Kubose, Holyoak, & Hummel, 2002).

**Advanced beginner (Surface structure)**. The advanced beginner stage represents a mental structure in which an adequate amount of contextual knowledge is recognized, but his or her knowledge lacks the building of a proper knowledge structure associated with principles. Otherwise, some instructed principles (key concepts/abstract knowledge) may exist but are not properly connected with one another. Accordingly, two types of mental structure are assumed: (a) mental modes in this stage have similar surface features with those of a reference model but not with structure and semantic features; or (b) there is a high similarity of semantic features but dissimilarity in surface and structure features between a student model and a reference model.

**Competent learner (Deep structure)**. A competent learner comes to identify key concepts underpinning the situations and thus organize the surface features. However, his or her mental structure still has missing relations among key variables. In other words, learners create either complex knowledge structures or an appropriate set of principles accompanied by a significant number of concepts and relations. There are likely two types of deep structure: (a) one has an adequate structural complexity along with a proper surface fit, which is not necessary to guarantee a semantic fit, however; and (b) the other consists of an appropriate number of contextual and principle concepts, but that are not well-structured in a proper manner.

**Proficient learner (Semantically deep structure)**. The next stage is the proficient learner stage in which learners conceptualize a sufficient problem space. This study regards experts as persons at the level of proficient performance. Mental models in this stage are assumed to be well-featured at all levels (surface, structure, and semantic). In addition, there is possibly another type of knowledge structure in which a significant number of principles creates a cohesive structure but with a small total number of concepts (surface). This model is supported by the claim that experts sometimes create mental models having an ‘optimal’ rather than 'maximum' number of concepts and relations that are very efficient (Glaser, Abelson, & Garrison, 1983; Glaser, 1992).

**Intuitive Expert (Advanced semantic structure)**. Dreyfus and Dreyfus (1986) regard the level of intuitive expert as somewhat mysterious ─not well understand, not able to provide clear support for. At this level, intuitive decision-making takes place based on an advanced semantic structure unlikely to theorize its measurable structure at this point (Dreyfus & Dreyfus, 2005). The difference between logical thinking (the proficient learner) and intuitive decision-making (the expert learner) toward problem-solving is not easily discerned by investigating a single set, or a few sets, of mental observations such as concept models because the measurable features of intuitive experts' mental models are still not well-understood. Admittedly, experts may not be fostered solely by instruction in a domain, for experiences both before and after instruction may be more influential in the making of an expert.

## Monitoring Learning Progress

### Detecting Stage Transitions

Changes in the stages of learning progress can provide information about the effects of an instructional intervention as well as about an individual's state of learning. Any instructional intervention in problem-solving learning may, to some extent, direct learners to improve their knowledge and skills. That is, interventions affect mental model changes. A learning environment in which teachers have diagnostic information about their students and provide formative feedback catered to the individual student's needs might be an ideal setting. No matter what intervention is designed to improve problem-solving knowledge and skills, it is important to see the learner's progress in a longitudinal manner so that one can evaluate the effects of an instructional intervention. The proposed framework hypothesizing stage-sequential learning progress provides a diagnostic model; further validation and research using this model is of course required.

**Possible Regression of Learning Progress**

We can anticipate that most students proceed through a positive learning progress from lower stages towards higher stages when they have appropriate instructional support, such as individualized feedback. In contrast, two different patterns can appear as follows:

**Expertise reversal effect**. The expertise reversal effect actually denotes that integrated information (e.g., text with diagram), which is designed to be beneficial for learning, may provide redundant information to expert learners, thereby hindering their ability to learn new knowledge (Kalyuga, Chandler, & Sweller, 1998; van Gog, Ericsson, Rikers, & Paas, 2005). In this paper, the expertise reversal effect is used as a general term indicating the unexpected effect of increasing expertise in learning and instruction. For example, in the context of measurement of mental models, the expertise reversal effect may cause an assessment of mental models to be dysfunctional. Suppose that a reference model for a physics problem is developed by only considering the classical physics theory (i.e., Newtonian mechanics). This is done based on the assumption that the target students are too immature to deal with more advanced theories, and the assessment will generate incorrect diagnostic information in the case of an advanced learner's response based on the theory of relativity or quantum theory.

**Reversion to an earlier stage**. Reversion to an earlier stage may be possible. For example, according to Vosniadou and Skopeliti (2005), children who believe the earth is a rectangular physical object require a slow and gradual process to obtain a scientific understanding, that is, to conceive of the earth as a spherical solar object. It is possible that some students fail to accomplish a conceptual change toward a scientific model of the earth and then revert to their naïve belief established from their everyday experiences reinforcing their model that the ground is flat and underneath them and, in contrast, the sky and solar objects are above.

**Reversion by expertise discordance**. We can assume another reversion affected by conflicting expertise even without degraded performance. For example, when a student in a South Korean high school whose family has defected from North Korea is solving an economic problem, the student may progress to some degree in conceptualizing a problem space based on capitalistic economics. However, at a certain point, the student may return to his/ her former expertise about Marxist economics to understand economic problems. Therefore, the student's response may appear backward. In that case, reverting to an earlier stage is not necessarily the same as degraded performance.

**Stay at a stage**. In some cases we may see no movement among stages. Although learners are given instructions and feedback, they may stagnate without more progress in problem solving. Two situations can be envisioned. Problem solving in a learning context is a goal-oriented activity that progresses toward learner acquisition of a reference model. These goals are external. A student may decide to ignore goals or reject the given feedback on his or her prior performance (e.g., prior problem conceptualization) (Sadler, 1989). In addition, low performing, self-efficacious students may experience a negative affect such as decreased motivation when they continuously receive negative feedback due to a lack of proper concepts in their understanding (Kernis, Broker, & Frankel, 1989). In these cases, progressing forward through stages may not take place.

**Learning Transfer as a Learning Progress**

The framework of stage-sequential learning progress ends with the expert stage. The expert stage is characterized as not only obtaining expertise in a particular domain, but also including the ability to transfer what an expert knows in one domain to solve problems in other contexts (Gentner, Loewenstein, & Thompson, 2003).

Although it is a common belief that people adapt their prior knowledge to solve new problems, the studies of transfer have taken diverse perspectives that seem to locate in a continuum with two polarized ends (e.g., Barnett & Ceci, 2002; Bransford & Schwartz, 1999; Gentner, Holyoak, & Kokinov, 2001; Gentner et al., 2003; Lave, 1988; Lobato, 2006; Reeves & Weissberg, 1994; Salomon & Perkins, 1989; Singley & Anderson, 1989). On one end, there is the notion of *identical elements* that are shared components between original learning and transfer situations. The extent of shared features determines the occurrence of transfer (That is the foundation of classical perspective; Thorndike, 1906; Cox, 1997). On the other end, according to a situated cognition standpoint, Lave (1988) asserted that knowledge cannot be detached from the specific situation in which it is acquired so that situation-specific knowledge cannot transfer. The framework of the learning progress associated with the theory of mental models possibly reconciles this classical view with alternative approaches.

Mental models for new situations may be created through an analogical thinking process which consists of selecting analogous models, comparing the original models with new situations, and modifying and simulating current mental models (Johnson-Laird, 1983; Norman, 1983; Seel, 2003). In that sense, the theory of mental models admits the notion of analogical transfer (Bransford, Brown, & Cocking, 2000; Gentner et al., 2001; Sternberg & Frensch, 1993).

In addition, mental models are domain-specific and situation-sensitive (Garnham, 1987, 2001). That is, key principles in mental models can be best interpreted in relation with surface features. In that sense, when transfer occurs, de-contextualized abstract knowledge might not be merely transferred. Rather, the original mental models as a whole might affect a new model in a new context. This view cannot only admit the role of key principles in transfer, but can also be reconciled with the critique such as how the classical transfer approach separates knowledge from situations (Lobato, 2006).

Supposing that assessment technologies, which can detect learner progress by embedding a tool visualizing mental models, are invented based on the suggested framework, it is possible to investigate transfer with the more accurate and rapid measures frequently used in a longitudinal study of cognitive change (e.g., Lemaire & Siegler, 1995). For example, a technique visualizing mental models shows the structural accuracy of learners' understanding (accuracy), and diagnosing learning stages in multiple occasions enable researchers to determine when learners reach the expected stage (speed).

**A Scenario**

A set of problem situations is carefully selected and developed to teach ecological relationships in a biology class. These complex problems have differing contexts but encompass the same key variables (i.e., population, nutrients, and predators). It is assumed that the problem scenarios have their own reference models and are the same in their levels of difficulty and complexity. For each problem situation, learners encounter multiple tests to measure their problem conceptualization. The problems are entitled as follows:

- *Crown-of-thorns starfish*
- *Habu (a viper) and mongoose in Okinawa*
- *Sharp drop of deer population in Georgia*
- *Disappearing iguana in the Galapagos Islands*
- *The attack of bass at the lakes in South Korea*

In problem-solving situations, acquired knowledge and problem-solving skills are expected to be transferred from one situation to the next. The expectation is that learners build their mental models representing the three key variables (i.e., population, nutrients, and predators) and their relationships across problem contexts.

The generalizability of specific problem-solving abilities can be anticipated based upon the continuous success in obtaining reference models of a set of similar problem situations and the speed of reaching the highest stage of learning progress. For example, in the given experimental scenario, most learners will likely have more difficulty in, and spend more time on, solving the first problem. Their stage transition may proceed systematically. In the second problem, although they progress without skipping stages, they may reach the target stage faster. In the third and fourth scenarios, some students may present a first response that begins at a higher point and skips the lower stages.

Finally, proficient students may solve the last problem very quickly. The series of examinations provide meaningful evidence: as students successively build a target-understanding of diverse problem situations, the speed to reach the target stage increases through solving subsequent problems. Based on this evidence, one can conclude that students acquire the expected problem-solving knowledge and skills that are transferred across the assigned problems. Namely, the application of particular problem-solving knowledge and skills towards a larger class of problems is also likely to be successful.

## Empirical Studies of the Theoretical Suggestions

This study discussed theoretical models of assessing learning progress rather than proposing certain assessment tools and methods. Theoretical suggestions in specific include (a) ways of building a student and reference model, (b) three features of knowledge structure, and (c) a framework of learning progress. There have been three studies as initial efforts to validate the suggestions (Author, 2011a, 2011b, and 2011c). Some findings of the studies are briefly introduced here, accompanied by related comments.

### The Problem-Solving Task

The author (Author, 2011a, 2011b, and 2011c) gathered data from 136 undergraduate students enrolled in a course at a university in the southern United States and seven professors teaching at a major university in the United States. All participants made written responses to a specific complex problem. The task provided a simulated situation in which students were assumed to be participating in an evaluation project, the purpose of which was to investigate an unsuccessful project that had as its goal adapting a technology (i.e., a tablet PC) for classroom teaching. The task the author used provides an example of problem cases that could be used in assessment and instruction.

**Reference Modeling**

The author (2011a, 2011b) included a reference model building procedure with which an expert model was successfully created in accordance with the suggestion of this study. In particular the author employed the Delphi survey procedure (Goodman, 1987; Hsu & Sandford, 2007; Okoli & Pawlowski, 2004). The panel composed of seven professors agreed with a reference model through three iterations of the Delphi survey to develop a refined model.

All panel members in the first round created their own response to the problem. Admittedly, diverse perspectives were observed in their initial responses that seemed not convergent but contrasting, even though there were some points on which they agreed. That observation was congruent with the claim that even experts elicit multiple representations of an ill-structured problem according to their own experiences (e.g., Jonassen, 1997). However, the Delphi procedure helped the panel learn from each other and achieve a consensus on the best understanding to the problem. That result proved that a reference model of an ill-structured problem can be created with proper methodological supports such as the Delphi procedure (Goldsmith & Kraiger, 1997; Spector, 2008a).

**Three Features of Knowledge Structure**

This study has proposed three features of knowledge structure (3S): Surface, structure, and semantic. The author (2011c) validated the three features of knowledge structure using the Confirmatory Factor Analysis (CFA). The author defined 10 parameters of concept maps obtained from the maps' structure and then associated the parameters with three features of knowledge structure that are assumed to be latent factors in the CFA models. The validation procedure includes sequential evaluation of a single factor model with a correlated group factor model. A single factor model was poor (CFI<0.90, NNFI<0.90). In contrast, the results of the CFA demonstrated that there is a three-dimensional feature of knowledge structure with good-fit indices (e.g., CFI>0.90, NNFI>0.90) (see Table 3).

Table 3.

*Summary of Fit Indices*

| Models | $\chi^2(df)$ | $\chi^2/(df)$ | CFI | NNFI | RMSEA | SRMR | AIC | ABIC |
|---|---|---|---|---|---|---|---|---|
| Single factor | 699(35) | 19.90 | 0.49 | 0.34 | 0.36 | 0.14 | -2518 | -2430 |
| Three factor | 96(26) | 3.69 | 0.94 | 0.90 | 0.14 | 0.18 | -3157 | -3042 |

Note. Indices (their expected values) are: $\chi 2$(df) =Chi-square statistics and degrees of freedom for test of model fit (equal to 0); $\chi 2/(df)$ =the ratio of Chi-square statistic to the degrees of freedom (equal to 1), CFI=comparative fit index(>0.90), NNFI=non-normal fit index (a.k.a., Tucker-Lewis index)(>0.90), RMSEA=root square error of approximation (<0.05), SRMR=standardized root mean square residual (<0.05), AIC(Akaike Information Criterion (close to 0, smaller the better), ABIC(Adjusted Bayesian Information Criterion) (close to zero, smaller the better)

**Stages of Learning Progress**

The conceptualized model of learning progress was investigated in the author's (2011c) study. The author defined a set of measures indicating the levels of the features of knowledge structure. Relations between the measures and the features of knowledge structures were determined based on theoretical assumptions as well as empirical evidence obtained from the aforementioned CFAs.

Stages in the learning progress are inferred rather than directly observed. Thus, qualitative stages of learning progress are labeled latent classes because of their psychometric characteristics. Accordingly, latent class model (LCM) methods were employed. In particular, the study employed Log-linear Cognitive Diagnostic Model (LCDM). LCDMs are restricted latent class models that allow latent class models to place linear restrictions on the log-linear parameters (Rupp, Templin, & Henson, 2010). It is important to note that LCDM requires a substantive theoretical model so that researchers can interpret statistical classifications as meaningful latent classes. The hypothetical relations between the three features of knowledge structure and a set of measures in the study provided a theoretical model for LCDM analysis.

Table 4

*Posterior Probabilities of Class Membership for the Stages of Learning Progress*

| Stage | Final Class Counts | Posterior Probability |
|---|---|---|
| Novice | 110.86033 | 0.77525 |
| Advanced beginner | 0.0009 | 0.0000 |
| Competent Learner | 0.00152 | 0.00001 |
| Proficient Learner | 32.1325 | 0.22474 |

$X^2$ and $G$ statistic proved that the students proceeded toward an expert-like knowledge structure through the suggested levels of learning progress ($p > .05$). As shown in Table 4, all stages were present. A large number of respondents were classified as novices or proficient learners, which resulted from positively correlated attributes (i.e., the three features of knowledge structure) similar with most assessment situations (Rupp, Templin, & Henson, 2010). However, the advanced beginner and competent learner stage were extremely small. Considering that study was an initial validation research, further studies with an adequate number of samples are desired in diverse conditions.

## Conclusion

### Implications for Research and Practice

Engineering personalized learning has been studied in reference to adaptive instruction, (e.g., Lee & Park, 2007) which is an attempt to provide an individualized or group (when students share similar characteristics) learning environment. Creating adaptive learning environments necessitates knowing the extent to which students understand the assigned problem situations and the changes in their levels of understanding. In this paper, theories for learning progress are explored in reference to problem conceptualization, a framework of cognitive changes in expertise development, and in the learning-transfer in problem-solving situations. The findings of this study should continue to inform subsequent research.

First, theoretical suggestions in this study include some measurable attributes for determination of levels of mental models. The three features (3S) of knowledge structure can be elaborated to the design and development of assessment methodologies. For instance, the measures used in the literature (Ifenthaler, Masduki, & Seel, 2009; Ifenthaler & Seel, 2005; Schlomske & Pirnay-Dummer, 2008) can be extended, including newly defined measures, and then their non-linear patterns and dynamic relations can be further investigated.

Second, as a basis for detecting and validating stages of learning progress, this study provides a theoretical framework entitled a stage-sequential model of learning progress. The framework can be a diagnostic model for a formative assessment technology and continue to further validation studies so as to find a best-fit model accounting for changes in learner understanding in response to ill-structured complex problem situations.

Third, the suggested framework of learning progress can best be fit to the use for tracking longitudinal changes in learning when regarding learning progress as transitions from one stage to another. Collins and Wugalter (1992) pointed out that psychological research and theory is increasingly turning to longitudinal studies, which monitors development by following individuals over time. Longitudinal studies based on the given framework are useful for evaluating the effectiveness of instruction or detecting an individual's trajectory and then determining proper educational supports to a certain stage.

Fourth, this study can contribute to assessment technology development. According to the theory of mental models, a mentally represented problem space is a structure including diverse relationships. Thus, assessment tools need to be adapted for the complex, dynamic structure of mental models so that diagnostic, formative information becomes more precise. As mentioned earlier, the proposed framework of learning progress can be elaborated as specific measurement methodologies and then developed into automated assessment technologies for complex problem-solving tasks. Automated assessment technologies could give teachers a sense of their students' learning that leads to better feedback and support. In addition, it is expected that assessment technology development facilitates multi-disciplinary research including computational linguistics, computer sciences, educational statistics, and instructional science.

**Suggestions for Future Studies**

First, the model of learning progress in this study only deals with the stages of learning progress preceding the intuitive expert level. Intuitive decision-making toward problem-solving is not easily discerned by investigating a single set, or a few sets of mental observations such as concept models, because the measurable features of intuitive experts' mental models are still not well-understood. Thus, theoretical suggestions that include some measurable attributes for determination of intuitive expert level mental models are requested.

Second, regression in learning progress raises a few concerns. For example, considering the expertise reversal effect, an advanced learner's unpredicted response could have assessment method dysfunctional. Designers should take into account advanced responses, which exceed their expectations, when designing problem cases and reference models.

Third, this study discussed the assessment model to diagnose domain knowledge as an internally represented problem situation. It is generally accepted that human cognition includes meta-cognition and motivation. Necessarily, it requires investigating how the two cognitive domains influence or interact with the proposed stages of learning progress. Furthermore, it could be assumed that meta-cognition and motivation proceed through qualitatively different stages, just as general cognition is assumed to do.

Finally, reverse progress implies that learning progress is not explained purely by cognitive factors but is influenced by intertwined effects that include non-cognitive factors (e.g., interest and self-efficacy). As mentioned earlier, low interest, self-efficacious students may remain stuck in a stage or move back to lower stages due to their ignorance of learning goals or the feedback provided (Kernis et al., 1989; Sadler, 1989). In order to understand the learning progress and provide better formative support, answers need to be supplied regarding the relationships among cognitive and non-cognitive factors in the learning progress. Following are some possible questions. What non-cognitive factors are related to developing expertise? To what extent is each non-cognitive factor associated with the change in learning stages? Similar to mental models as indicators of cognitive changes, can non-cognitive factors be classified in sequential stages? Can the five stage model of learning progress be a shared model that classifies non-cognitive factors? Can we establish an integrated model of learning progress that includes cognitive and non-cognitive factors? How can we determine a learner's stage based on an integrated perspective? What instructional and feedback strategies can be elaborated based on the framework of learning progress that considers both cognitive and non-cognitive factors?

**Closing Thoughts**

If we wish to create an instructional program aimed at developing expertise in particular domains, we need to understand students' levels of understanding, monitor their progress, and provide personalized feedback. Students in different stages may have different needs because of the diverse states in their mental representations. In other words, instruction needs to be adaptive to individual differences.

This focused literature review and conceptual development paper provides theoretically grounded guidelines to address some issues of assessing learning progress based on the theory of mental models, developmental psychology, and the development of expertise. For example, the theory of mental models provides practical suggestions on how to elicit learner models and how to build reference models for both structured and ill-structured problem-solving tasks. The research about expertise development presents plausible frameworks for qualitatively distinct developmental stages through which learners proceed. These theoretical findings leave significant practical questions, and theory has more value when it contributes to improving learning. For instance, instructional and feedback strategies associated with each stage of learning progress require elaboration. Assessment results should be accompanied by instructional supports suited to each individual or group of students. Instructional models based on diagnostic assessment can lead to the development of diverse instructional applications, such as improved intelligent tutoring systems.

**References**

Alexander, P. A. (2003). The development of expertise: The journey from acclimation to proficiency. *Educational Researcher, 32*(8), 10-14.

Alexander, P. A. (2004). A model of domain learning: Reinterpreting expertise as a multidimensional, multistage process. In D. Y. Dai & R. J. Sternberg (Eds.), *Motivation, emotion, and cognition: Integrative perspectives on intellectual functioning and development* (pp. 273-298). Mahwah, NJ: Lawrence Erlbaum Associates, Publishers.

Anderson, J. R. (1980). *Cognitive psychology and its implications*. New York: Freeman.

Anzai, Y., & Yokoyama, T. (1984). Internal models in physics problem solving. *Cognition and Instruction, 1*, 397-450.

Axelrod, R. (1976). *Structure of decision: The cognitive maps of political elites*. Princeton, N.J.: Princeton University Press.

Barnett, S. M., & Ceci, S. J. (2002). When and where do we apply what we learn? A taxonomy for far transfer. *Psychological Bulletin*, *128*(4), 612-637.

Bransford, J. D., Barclay, J. R., & Franks, J. J. (1972). Sentence memory: A constructive versus interpretive approach. *Cognitive Psychology, 3*, 193-209.

Bransford, J. D., Brown, A. L., & Cocking, R. R. (Eds.). (2000). Learning and transfer. In *How people learn: Brain, mind, experience, and school* (pp. 31–78).Washington, DC: National Academy Press.

Bransford, J. D., & Franks, J. J. (1972). The abstraction of linguistic ideas. *Cognitive Psychology*, 2, 331-350.

Bransford, J. D., & Johnson, M. K. (1972). Contextual prerequisites for understanding: Some investigations of comprehension and recall. *Journal of Verbal Learning and Verbal Behavior, 11*(6), 717-726. doi:16/S0022-5371(72)80006-9

Bransford, J. D.,& Schwartz, D. L. (1999). Rethinking transfer: A simple proposal with multiple implications. In A. Iran-Nejad & P. D. Pearson (Eds.), *Review of research in education* (Vol. 24, pp. 61–100). Washington, DC: American Educational Research Association.

Bruner, J. S. (1961). The act of discovery. *Harvard Educational Review, 31*, 21-32.

Cañas, A. J. (2009). *What are Propositions? ... from a Concept Mapping Perspective*. Retrieved July 31, 2011, from http://cmap.ihmc.us/docs/Proposition.html

Carley, K., & Palmquist, M. (1992). Extracting, representing and analyzing mental models. *Social Forces, 70*, 215-225.

Carver, S. M. (2006). Assessing for deep understanding. In R. K. Sawyer (Ed.), *Cambridge handbook of the learning science* (pp. 205-221). New York: Cambridge University Press.

Chen, Z., & Siegler, R. S. (2000). Intellectual development in childhood. In R.Sternberg (Ed.) *Handbook of intelligence* (pp. 92-116). New York: Cambridge.

Chi, M.T.H. (2006). Two approaches to the study of experts' characteristics. In K.A. Ericsson, N. Charness, P. Feltovich, & R. Hoffman (Eds.), *Cambridge Handbook of Expertise and Expert Performance* (pp. 121-130), Cambridge University Press.

Chi, M. T. H., Glaser, R., & Farr, M. (Eds.). (1988). *The nature of expertise*. Hillsdale, NJ: Erlbaum.

Clariana, R. B., & Wallace, P. (2007). A computer-based approach for deriving and measuring individual and team knowledge structure from essay questions. *Journal of Educational Computing Research*, *37*(3), 211-227. doi:10.2190/EC.37.3.a

Collins, A. & Gentner, D. (1987). How people construct mental models. In D. Holland & N. Quinn (Eds.), *Cultural models in language and thought*, (pp. 243-265). Cambridge, MA: Cambridge University Press.

Collins, L. M., & Wugalter, S. E. (1992). Latent class models for stage-sequential dynamic latent variables. *Multivariate Behavioral Research, 27*(1), 131-157.

Cox, B. D. (1997). The rediscovery of the active learner in adaptive contexts: A developmental-historical analysis of transfer of training. *Educational Psychologist, 32*(1), 41–55.

Craik, K. J. W. (1943). *The Nature of Explanation*. Cambridge UK: Cambridge University Press.

Cronbach, J. L. (1957). The two disciplines of scientific psychology. *American Psychologist, 12*, 671-684.

Gijbels, D., Dochy, F., den Bossche, P. V., & Segers, M. (2005). Effects of problem-based learning: A meta-analysis from the angle of assessment. *Review of Educational Research*, *75*(1), 27-61.

Dochy, F., Segers, M., Van den Bossche, P., & Gijbels, D. (2003). Effects of problem-based learning: a meta-analysis. *Learning and Instruction, 13*(5), 533-568. DOI:10.1016/S0959-4752(02)00025-7

Dreyfus, H. L., & Dreyfus, S. E. (2005). Peripheral vision: Expertise in real world contexts. *Organization Studies (after Jan 1, 2003)*, *26*(5), 779-792.

Dreyfus, H. L., & Dreyfus, S. E., with Athanasiou, T. (1986). *Mind over machine: The power of human intuition and expertise in the era of the computer*. Oxford, UK: B. Blackwell.

Ericsson, K. A. (2003). The acquisition of expert performance as problem solving: Construction and modification of mediating mechanisms through deliberate practice. In J. E. Davidson & R. J. Sternberg (Eds.), *The psychology of problem solving* (pp. 31-83). New York: Cambridge University Press.

Ericsson, K. A. (2005). Recent advances in expertise research: A commentary on the contributions to the special issue. *Applied Cognitive Psychology, 19*, 233-241.

Ericsson, K. A. (2006). The influence of experience and deliberate practice on the development of superior expert performance. In K. A. Ericsson, N. Charness, P. Feltovich, & R. R. Hoffman, R. R. (Eds.), *Cambridge handbook of expertise and expert performance* (pp. 685-706). Cambridge, UK: Cambridge University Press.

Ericsson, K., & Simon, H. (May 1980). Verbal reports as data. *Psychological Review, 87*(3), 215–251. doi:10.1037/0033-295X.87.3.215

Ericsson, K., & Simon, H. (1993). *Protocol analysis: Verbal reports as data (2nd ed.)*. Boston: MIT Press. ISBN 0262050293.

Festinger, L. (1962). Cognitive dissonance. *Scientific American, 207*(4), 93-102.

Fischer, K. W., & Silvern, L. (1985). Stages and individual differences in cognitive development. *Annual Review of Psychology, 36*, 613-648.

Flavell, J. H. (1985). *Cognitive development* (2nd ed.). Englewood Cliffs, NJ: Prentice-Hall.

Flavell, J. H. (1992). Cognitive development: Past, present, and future. *Developmental Psychology, 28*(6), 998-1005.

Flavell, J. H., & Miller, P. H. (1998). Social cognition. In W. Damon & D. Kuhn & R. S. Siegler (Eds.), *Handbook of child psychology: Vol. 2. Cognition, perception, and language* (pp. 851–898). New York: Wiley.

Forbus, K. D., Gentner, D., & Law, K. (1995). MAC/FAC: A model of similarity-based retrieval. *Cognitive Science, 19*, 141–205.

Garnham, A. (1987). *Mental models as representations of discourse and text*. Chicheser: Ellis Horwood Ltd.

Garnham, A. (2001). *Mental models and the interpretation of anaphora*. Hove, UK: Psychology Press.

Gentner, D., Holyoak, K. J., & Kokinov, B. N. (2001). *The analogical mind*. Cambridge, MA: MIT Press.

Gentner, D., Loewenstein, J., & Thompson, L. (2003). Learning and transfer: A general role for analogical encoding. *Journal of Educational Psychology*, *95*(2), 393-408. doi:10.1037/0022-0663.95.2.393

Gentner, D., & Medina, J. (1998). Similarity and the development of rules. *Cognition, 65*, 263–297.

Gentner, D., & Stevens, A. L. (1983). *Mental models*. Hillsdale, NJ: Lawrence Erlbaum.

Gijbels, D., Dochy, F., den Bossche, P. V., & Segers, M. (2005). Effects of problem-based learning: A meta-analysis from the angle of assessment. *Review of Educational Research, 75*(1), 27-61.

Glaser, E. M., Abelson, H. H., & Garrison, K. N. (1983). *Putting knowledge to use: Facilitating the diffusion of knowledge and the implementation of planned change* (1st ed.). San Francisco, CA: Jossey-Bass.

Goldsmith, T. E., & Kraiger, K. (1997). Applications of structural knowledge assessment to training evaluation. In J. K. Ford (Ed.), *Improving training effectiveness in organizations* (pp. 73–95). Mahwah, NJ: Lawrence Erlbaum Associates.

Goodman, C. M. (1987). The Delphi technique: a critique. *Journal of Advanced Nursing, 12*(6), 729-734.

Greeno, J.G. (1989). Situations, mental models, and generative knowledge. In D. Klahr & K. Kotovsky (Eds.), *Complex information processing* (pp. 285-318). Hillsdale, NJ: Erlbaum.

Hoffman, R. R. (1998). How can expertise be defined?: Implications of research from cognitive psychology. In R. Williams, W. Faulkner, & J. Fleck (Eds.), *Exploring expertise* (pp. 81-100). New York: Macmillan.

Holyoak, K. J., & Koh, K. (1987). Surface and structural similarity in analogical transfer. *Memory & Cognition, 15*, 332–340.

Hsu, C. & Sandford, B. A. (2007). The Delphi Technique: Making Sense of Consensus. *Practical Assessment Research & Evaluation, 12*(10). Available online: http://pareonline.net/getvn.asp?v=12&n=10

Ifenthaler, D. (2006). *Diagnose lernabhängiger Veränderung mentaler Modelle. Entwicklung der SMD-Technologie als methodologische Verfahren zur relationalen, strukturellen und semantischen Analyse individueller Modellkonstruktionen*. Freiburg: Universitäts-Dissertation.

Ifenthaler, D. (2010). Relational, structural, and semantic analysis of graphical representations and concept maps.Educational Technology Research & Development, 58(1), 81-97. doi:10.1007/s11423-008-9087-4.

Ifenthaler, D., Masduki, I., & Seel, N. M. (2009). The mystery of cognitive structure and how we can detect it: tracking the development of cognitive structures over time. *Instructional Science*. doi:10.1007/s11251-009-9097-6

Ifenthaler, D., & Seel, N. M. (2005). The measurement of change: Learning-dependent progression of mental models. *Technology, Instruction, Cognition, and Learning*, *2* (4), 321-340.

Johnson-Laird, P.N. (1983). *Mental models: Towards a cognitive science of language, inference, and consciousness*. Cambridge: Cambridge University Press.

Johnson-Laird, P.N. (2005a). Mental models and thoughts. In K. J. Holyoak (Ed.), *The Cambridge handbook of thinking and reasoning* (pp. 185-208). Cambridge University Press.

Johnson-Laird, P.N. (2005b). The history of mental models. In K. I. Manktelow, & M. C. Chung (Eds), *Psychology of reasoning: theoretical and historical perspectives* (pp. 179-212). Psychology Press.

Jonassen, D. H. (1997). Instructional design models for well-structured and ill-structured problem-solving learning outcomes. *ETR&D, 45*(1), 65-94.

Jonassen, D. H. (2000). Toward a design theory of problem solving. *ETR&D, 48*(4), 63-85.

Jonassen, D. H., Beissner, K., & Yacci, M. (1993). *Structural knowledge: techniques for representing, conveying, and acquiring structural knowledge*. Hillsdale, NJ: Lawrence Erlbaum Associates.

Judd, C. H. (1908). The relation of special training to general intelligence. *Educational Review, 36*, 28–42.

Kail, R. V. (2004). Cognitive Development Includes Global and Domain-Specific Processes. *Merrill Palmer Quarterly Journal of Developmental Psychology, 50*(4), 445-455.

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

Katz, J. J., & Postal, P. M.(1964). *An integrated theory of linguistic descriptions*. Cambridge: M.I.T. Press.

Kendler, H. H., & Kendler, T. S. (1962). Vertical and horizontal processes in problem solving. *Psychological Review, 69*, 1-16.

Kernis, M. H., Brockner, J., & Frankel, B. S. (1989). Self-esteem and reactions to failure: The mediating role of overgeneralization. *Journal of Personality and Social Psychology, 57*, 707–714.

Kieras, D.E., & Bovair, S. (1984). The role of a mental model in learning to operate a device. *Cognitive Science, 8*, 255-273.

Author (2011a). --------------

Author (2011b). ---------------

Author (2011c). ---------------

Kintsch, W., & van Dijk, T. A. (1978). Toward a model of text comprehension and production. *Psychological Review, 85*(5), 363-394. doi:10.1037/0033-295X.85.5.363

Kubose, T. T., Holyoak, K. J., & Hummel, J. E. (2002). The role of textual coherence in incremental analogical mapping. *Journal of memory and language, 47*(3), 407–435.

Lave, J. (1988). *Cognition in practice: Mind, mathematics, and culture in everyday life.* Cambridge, United Kingdom: Cambridge University Press.

Lee, J., & Park, O. (2007). Adaptive instructional systems. In J. M. Spector, M. D. Merill, J. van Merrienboer & M. P. Driscoll (Eds.), *Handbook of research for educational communications and technology* (pp. 469-484). Routledge: Taylor & Francis Group.

Lemaire, P, & Siegler, R. S. (1995). Four aspects of strategic change: Contributions to children's learning of multiplication. *Journal of Experimental Psychology: General, 124* (1), 83-97.

Lobato, J. (2006). Alternative perspectives on the transfer of learning: History, issues, and challenges for future research. *Journal of the Learning Sciences*, *15*(4), 431-449.

Mayer, R. E. (1989). Models for understanding. *Review of Educational Research, 59*(1), 43-64.

Newell, A. (1990). *Unified theories of cognition*. Cambridge, MA: Harvard University Press.

Newell, A., & Simon, H. (1972). *Human problem solving*. Englewood Cliffs, NJ: Prentice Hall.

Norman, D. (1983). Some observations on mental models. In D. Gentner & A. L. Stevens (Eds.), *Mental models* (pp. 7-14). Hillsdale, NJ: Erlbaum.

Norman, D. A., Gentner, D. R., & Stevens, A. L. (1976). Comments on learning schemata and memory representation. In D. Klahr (Ed.), *Cognition and instruction* (pp. 177–196). Hillsdale, NJ: Lawrence Erlbaum Associates.

Okoli, C., & Pawlowski, S. D. (2004). The Delphi method as a research tool: an example, design considerations and applications. *Information & Management, 42*(1), 15-29. doi:10.1016/j.im.2003.11.002

Opfer, J. E., & Siegler, R. S. (2004). Revisiting preschoolers' living things concept: A microgenetic analysis of conceptual change in basic biology. *Cognitive Psychology, 49*, 301-332.

Piaget, J. (1964). Development and learning. In R. E. Ripple & V. N. Rockcastle (Eds.), *Piaget rediscovered* (pp. 7-20). Ithaca, NY: Cornell University.

Piaget, J. (1976). *Science of education and the psychology of the child*. New York: Orion Press.

Pirnay-Dummer, P. (2006). *Expertise und Modellbildung – MITOCAR*. Freiburg: Universitäts-Dissertation.

Pirnay-Dummer, P., Ifenthaler, D., & Spector, J. (2010). Highly integrated model assessment technology and tools.*Educational Technology Research & Development, 58*(1), 3-18. doi:10.1007/s11423-009-9119-8.

Pretz, J. E., Naples, A. J., & Sternberg, R. J. (2003). Recognizing defining, and representing problems. In J. E. Davidson & R. J. Sternberg, *The psychology of problem solving* (pp. 3-30). New York: Cambridge University Press.

Reeves, L. M., & Weisberg, R. W. (1994). The role of content and abstract information in analogical transfer. *Psychological Bulletin, 115*(3), 381–400.

Rumelhart, D. E., & Norman, D. A. (1978). Accretion, tuning and restructuring: Three model of learning. In R. L. Klatzky & J. W. Cotton (Eds.), *Semantic factors in cognition* (pp. 37–53). Hillsdale, NJ: Lawrence Erlbaum.

Rupp, A. A., Templin, J. L., & Henson, R. A. (2010). *Diagnostic Measurement: Theory, Methods, and Applications*. New York: The Guilford Press.

Sadler, D. R. (1989). Formative assessment and the design of instructional systems. *Instructional Science, 18*(2), 119-144.

Salomon, G., & Perkins, D. N. (1989). Rocky roads to transfer: Rethinking mechanisms of a neglected phenomenon. *Educational Psychologist, 24*, 113–142.

Schlomske, N., & Pirnay-Dummer, P. (2008). Model based assessment of learning dependent change during a two semester class. In Kinshuk, Sampson, D., & Spector, M. (Eds.), *Proceedings of IADIS International Conference Cognition and Exploratory Learning in Digital Age 2008*, Freiburg, Germany, pp. 45-53.

Schvaneveldt, R. W. (Editor) (1990). *Pathfinder associative networks: Studies in knowledge organization*. Norwood, NJ: Ablex Publishing.

Schvaneveldt, R.W., Durso, F.T., Goldsmith, T.E., Breen, T.J., & Cooke, N.M. (1985). Measuring the structure of expertise. *International Journal of Man-Machine Studies, 23,* 699-728.

Seel, N. M. (2001). Epistemology, situated cognition, and mental models: Like a bridge over troubled water. *Instructional Science, 29* (4-5), 403-427.

Seel, N. M. (2003). Model-centered learning and instruction. *Technology, Instruction, Cognition, and Learning, 1* (1), 59-85.

Seel, N. M. (2004). Model-centered learning environments: Theory, Instructional design, and ethics. In N. M. Seel & S. Dijkstra (Eds.), *Curriculum, plans, and processes in instruction design: International perspectives* (pp. 49-74). NJ: Lawrence Erlbaum Associates, Inc.

Seel, N. M., & Dinter, F. R. (1995). Instruction and mental model progression: Learner-dependent effects of teaching strategies on knowledge acquisition and analogical transfer. *Educational Research and Evaluation, 1*(1), 4-35.

Segers, M. (1997). An alternative for assessing problem-solving skills: The overall test. *Studies in Educational Evaluation, 23*(4), 373-398.

Shaklee, H. (1979). Bounded rationality and cognitive development: Upper limits on growth? *Cognitive Psychology, 11*, 327-345.

Shute, V. J., & Zapata-Rivera, D. (2007). Adaptive technologies. In J. M. Spector, M. D. Merill, J. van Merrienboer & M. P. Driscoll (Eds.), *Handbook of research for educational communications and technology* (pp. 227-294). Routledge: Taylor & Francis Group.

Simon, H. A., & Hayes, J. R. (1976). The understanding process: Problem isomorphs. *Cognitive Psychology, 8*, 165–190.

Siegler, R. S. (2005). Children's Learning. *American Psychologist, 60*, 769-778.

Siegler, R. S., & Klahr, D. (1982). When do children learn: The relationship between existing knowledge and the ability to acquire new knowledge. In R. Glaser (Ed.), *Advances in Instructional Psychology: Vol. 2* (pp. 121-211). Hillsdale, NJ: Erlbaum.

Siegler, R. S., Thompson, C. A., & Opfer, J. E. (2009). The logarithmic-to-linear shift: One learning sequence, many tasks, many time scales. *Mind, Brain, and Education, 3*, 143-150.

Singley, M. K., & Anderson, J. R. (1989). *The transfer of cognitive skill*. Cambridge, MA: Harvard University Press.

Smith, J. P., diSessa, A. A., & Roschelle, J. (1993). Misconceptions reconceived: A constructivist analysis of knowledge in transition. *The Journal of the Learning Sciences, 3*(2), 115-163.

Snow, R.E. (1990). New approaches to cognitive and conative assessment in education. *International Journal of Educational Research, 14* (5), 455–473.

Spector, J. M. (2004). Problems with problem-based learning: Comments on model-centered learning and instruction in Seel (2003). *Technology, Instruction, Cognition and Learning, 1*(4), 359-374.

Spector, J. M. (2008a). Cognition and learning in the digital age: Promising research and practice. *Computers in Human Behavior, 24*(2), 249-262.

Spector, J. M. (2008b). Expertise and dynamic tasks. In H. Qudrat-Allah, J. M. Spector, & P. I. Davidsen (Eds.), *Complex decision making: Theory and practice*. Berlin: Springer-Verlag.

Spector, J. M. (2008c). Complex domain learning. In H. H. Adelsberger, Kinshuk, J. M. Pawlowski, & D. Sampson (Eds.), *Handbook of information technologies for education and training* (pp. 261 – 275). Heidelberg: Springer.

Spector, J. M., & Koszalka, T. A. (2004). *The DEEP methodology for assessing learning in complex domains* (Final report to the National Science Foundation Evaluative Research and Evaluation Capacity Building). Syracuse, NY: Syracuse University.

Sternberg, R. J. (2008). Applying psychological theories to educational practice. *American Educational Research Journal, 45*(1), 150-165.

Sternberg, R. J.,& Frensch, P. A. (1993).Mechanisms of transfer. In D. K. Detterman&R. J. Sternberg (Eds.), *Transfer on trial: Intelligence, cognition, and instruction* (pp. 25–38).Norwood, NJ: Ablex.

Sugrue, B. (1995). A theory-based framework for assessing domainl-specific problem-solving ability. *Educational Measurement: Issues and Practice, 14*(3), 29-35. doi:10.1111/j.1745-3992.1995.tb00865.x

Taricani, E. M., & Clariana, R. B. (2006). A Technique for Automatically Scoring Open-Ended Concept Maps. *Educational Technology Research & Development, 54*(1), 65-82. doi:Article

Thorndike, E. L. (1906). *Principles of teaching*. New York: Seiler.

van Gog, T., Ericsson, K. A., Rikers, R. M., & Paas, F. (2005). Instructional design for advanced learners: establishing connections between the theoretical frameworks of cognitive load and deliberate practice. *ETR&D, 53*(3), 73-81.

Vosniadou, S., & Skopeliti, I. (2005). Developmental shifts in children's categorization of the earth. In B. G. Bara, L. Barsalou, & M. Bucciarelli (Eds.), *Proceedings of the XXVII Annual Conference of the Cognitive Science Society* (pp. 2325-2330).

Vosniadou, S., Vamvakoussi, X., & Skopeliti, I. (2008). The framework theory approach to the problem of conceptual change. In S. Vosniadou (Ed.), *International handbook of research on conceptual change* (pp. 3-34). New York: Routledge.

Vygotsky, L. (1934/1978). *Mind in society*. Cambridge, MA: Harvard University Press.

Werner, H. (1957). The concept of development from a comparative and organismic point of view. In D. B Harris (Ed.), *The concept of development: An issue in the study of human behavior* (pp. 125–148). Minneapolis, MN: University of Minnesota

Wood, P. K. (1983). Inquiring systems and problem structures: Implications for cognitive development. *Human Development, 26*, 249-265.