Cognitive Requirements for Learning with Open-Ended Learning Environments

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Open-ended learning environments (OELEs) use the capabilities of technology to provide students with opportunities to engage in authentic problem solving; generate, test, and revise hypotheses; explore and manipulate concepts; and reflect on what they know. By design, such environments require sophisticated levels of cognitive functioning. The purpose of this paper is to critically analyze assumptions underlying learner-centered, technology-based environments in light of how well learners appear to meet the cognitive demands for engaging them. Implications for design include the following considerations: (a) direct learner attention to key variables and visual cues; (b) prompt and guide connections to prior knowledge; and (c) provide explicit scaffolding of metacognition and teaching-learning strategies.

☐ Over the past decade, a marriage between technology and learner-centered theoretical perspectives—primarily those that are constructivist—has heralded opportunities for higher-order thinking and problem solving (Jonassen, 1999). Rapid advances in computer technologies have facilitated the development of electronic tools and resources that have, in turn, expanded the *opportunities* to empower student-centered alternatives. Although at face value the potential of these opportunities is compelling, the extent to which learners "mindfully" engage them is not at all certain. Salomon (1986) has cautioned against overrelying on theoretical assumptions regarding how learners might, or might not, mindfully engage information technologies.

The role of emerging technologies to support learner-centered understanding frequently has been discussed in the literature. For the purposes of this paper, technology-based environments that follow constructivist assumptions will be referred to broadly as open-ended learning environments (OELEs). Hannafin and others (Hannafin, Hall, Land, & Hill, 1994; Hannafin, Land, & Oliver, 1999) regard OELEs as environments that rely on technological tools and resources to support unique learning goals and knowledge construction. Typically, OELEs use the capabilities of technology to create environments wherein complex concepts can be represented, manipulated, and explored. Examples of OELEs range from use of hypermedia information systems to support information seeking and inquiry (Hill, 1999), to modeling, visualization, and simulation tools for virtual experimentation (de Jong & van Joolingen, 1998; Gordin & Pea, 1995), to microcomputer-based laboratories to represent hard-to-see concepts in real time, such as oscillatory motion (Kelly & Crawford, 1996).

Much of what has been written related to

ETR&D, Vol. 48, No. 3, 2000, pp. 61–78 ISSN 1042–1629

OELEs and constructivist environments emphasizes descriptive elements such as philosophical assumptions, case studies of specific examples, or methods, components, and features (Hannafin et al., 1994; Hannafin et al., 1999; Jonassen, 1999). What research that has been done on learning with OELEs often sheds a skeptical light. It is not uncommon to find inconsistencies between assumptions about what learners are expected to do and what they actually do. Some of the more discouraging research findings have included the following:

- Students have failed to substantially evolve theories or explanations, often retaining initial misconceptions (de Jong & Van Joolingen, 1998; Gyllenhaal & Perry, 1998; Land & Hannafin, 1997; Nicaise & Crane, 1999);
- Students have failed to engage in reflective thinking and metacognition during inquiry (Atkins & Blissett, 1992; Hill & Hannafin, 1997; Wallace & Kupperman, 1997);
- Students have failed to develop coherent explanations, as evidenced by superficial artifacts devoid of supporting evidence (Land & Greene, 2000; Nicaise & Crane, 1999; Oliver, 1999).

It appears, then, that despite the theoretical ideals of learning with OELEs, actual implementation of them is not always so laudatory. Given these limitations, it may be worthwhile to reconsider questions initiated by Salomon (1986)—How mindfully do learners engage information technologies? That is, "do they generate relevant hypotheses, plan ahead, compare alternatives, evaluate simulation outcomes, thoughtfully examine feedback, and think analytically when these opportunities are afforded and called for?" (p. 208).

OELEs are designed to support thinking-intensive interactions with limited external direction; hence, successful learning with OELEs is largely dependent on learners' voluntary cognitive engagement (Salomon, 1986). In this paper, I explore issues surrounding the cognitive demands of learners during interaction with OELEs. It is my contention that many of the problems reported in the literature are rooted in difficulties of learners to meet the psychological demands for learning with OELEs. Through explicit awareness of what we are expecting from learners cognitively, we should be in a better position to support the complexity that is inherent to learning with OELEs. Thinking-intensive interactions are not likely to be realized without external support of some form; thus understanding what these requirements are, and how they sometimes break down, are important next-step considerations for design of OELEs to support deeper levels of cognitive engagement.

Accordingly, the purpose of this paper is to critically analyze assumptions of OELEs in light of how well learners appear to meet the cognitive demands for engaging them. This analysis entails four dimensions. First, I identify capabilities and features of OELEs that are presumed to enhance specific cognitive competencies (e.g., computer tools for predicting, perspective building, planning etc.). Second, I analyze what is required cognitively by learners to take advantage of these opportunities. Third, based on an analysis of research findings, I examine problems and issues experienced by learners· with OELEs. Finally, I suggest implications for design that show promise to support deeper levels of cognitive engagement. In selecting research studies to analyze, I focused primarily on descriptive studies that allowed insight into the difficulties experienced by learners to generate meaning during learning with OELEs. In recognition of the formative nature of student-centered environments, I intentionally emphasized problems and issues that point to future implications for design.

The analyses presented in this paper are based on a cognitive perspective of the *learner as active constructor of meaning*. The fundamental psychological premise is that learners develop understanding through interactions with the surrounding environment, using a process of theory building to make sense of it (Piaget, 1976). That is, through observation, reflection, and experimentation, understanding evolves in response to interactions that continually confirm, challenge, or extend ongoing theories or beliefs (Hannafin et al., 1994; Land & Hannafin, 1996). Thus when immersed in environments that cultivate "learning by doing," learners access and apply related prior experiences and develop them through interacting with the environment. Accordingly, learning involves formulating conjectures, testing claims, and reconciling them based on evidence that supports or contradicts initial beliefs (Karmiloff-Smith & Inhelder, 1975; Piaget, 1976).

GAPS BETWEEN OPPORTUNITY AND REALITY: ANALYSIS OF OELE CAPABILITIES

Computer technology is often a central component of OELEs, because it is used to afford opportunities for learning that could not be accomplished without a computer (Pea, 1985). Computers, for instance, can represent phenomena in three dimensions; for example, protein and cell structures that can be rearranged and observed. Microworlds such as *Interactive Physics*™ and *ErgoMotion* allow learners to create virtual designs, manipulate variables, and observe results within simulated, gravity-free contexts. Other tools, such as the *Virtual Fly Lab*, permit learners to cross over nine fruit fly traits in ways that could not be accomplished through pencil and paper. With OELEs, technology is used in ways that extend how we can represent concepts (e.g., objects moving without gravity; 3-dimensional representations), and hence how learners can be supported to *think* about them (Pea, 1985).

Although technology can offer powerful learning opportunities, effectively realizing them is also tied to how intentionally and judiciously learners engage them (Perkins, 1985; Salomon, 1986). Underlying specific OELE designs are assumptions about what learners will actually do and how they will leverage technological capabilities to deepen understanding. In this section, I describe three components of technology-based OELEs to enhance understanding (adapted from Hannafin et al., 1999): (a) use of visualization or manipulation tools to facilitate experimentation of complex phenomena; (b) use of authentic contexts to foster connections between formal knowledge and everyday experience; and (c) use of resource-rich environments to support learner-centered inquiry. Each is analyzed in light of what opportunities are afforded by OELEs, what is required by learners to engage them, and what types of problems can transpire. Implications for design follow. Table 1 provides a summary of specific capabilities of OELEs, associated cognitive requirements, related problems and issues, and implications for design.

Use of Visualization or Manipulation Tools to Facilitate Experimentation of Complex Phenomena

OELEs often utilize technological capabilities to represent abstract or "hard-to-see" concepts. Frequently referred to as *visualization tools* (Gordon & Pea, 1995), computer graphics are used to produce pictorial similarities of phenomena that can be visualized and manipulated by learners. Examples range from use of data sets and satellite images to visualize climate (e.g., holes in the ozone layer) to microworlds or simulations that animate force and motion (e.g., objects moving in zero gravity) to graphical animations of time-based processes (e.g., microcomputer-based laboratories that generate real-time graphs of changes in temperature). The purpose of visualization tools is to help learners gain access to ideas that normally would be too complex or difficult to introduce otherwise. By representing a difficult concept visually, learners can be led to study new questions and ideas that they might not have considered without being able to "see" them (e.g., Why does the size of the ozone hole change regularly?) (Gordin & Pea, 1995).

Some environments allow learners not only to see visual representations but to manipulate them. For instance, mathematical equations can be visualized, manipulated, and rotated using tools such as the *Geometer's Sketchpad* or *Mathematica*, enabling learners to experiment with quantities. Also, with a thermodynamics simulation such as the *Computer as Learning Partner* (CLP) (Lewis, Stern, & Linn, 1993), learners can manipulate values such as surface area, insulating material, or initial temperature and see graphically how temperature changes over time. For instance, students could observe the cooling process of hot chocolate that is insulated by a styrofoam cup versus a steel cup and compare real-time graphs of temperature change.

Table 1 ☐ Summary of open-ended learning environment (OELE) capabilities, cognitive requirements, problems and issues, and implications

OELE Capabilities	*Cognitive Requirements*	*Problems and Issues*	*Implications for Design*
Use of visualization or manipulation tools to facilitate experimentation of complex phenomena.	*Generate, test, and refine theories, based on supporting evidence perceived from visual displays.* • Recognize whether changes in a visual display have occurred as a result of manipulating a variable (while holding others constant) (selective perception); • Discriminate which visual cues are relevant to attend to in a visual display; • Draw accurate conclusions from observations of visual cues (causal reasoning); • Relate conclusions to plausible explanations (inferencing; theory building).	*Limitations of novices to accurately perceive and interpret visual cues.* • Attending to, and attaching meaning to, irrelevant visual cues (Brungardt & Zollman, 1995; Gyllenhaal & Perry, 1998); • Drawing inaccurate conclusions from visual cues (Land & Hannafin, 1997); • Making biased observations of visual cues based on preconceptions (Chinn & Brewer, 1993; Gyllenhaal & Perry; Land & Hannafin, 1997).	*Direct learner attention to key variables and visual cues.* • Emphasize critical variables visually (Hannafin & Peck, 1988; Petre, 1995); • Enhance more objective comparison of different visual displays; (Roth, 1995; Tufte, 1983); • Provide explicit support for learners to interpret the meaning of visual representations (Foley, 1998; Gordin, Edelson, & Pea, 1996); • Use modeling, dialogue, or both to help learners attend to and interpret complex visual representations (Gordin et al., 1996).
Use of authentic contexts to foster connections between formal knowledge and everyday experience	*Integrate new and prior knowledge.* • Make voluntary references to examples, analogies, metaphors, prior knowledge, or personal experience to map new, classroom knowledge on to natural, everyday events (transfer; analogical reasoning); • Evolve initial, naive conceptions and explanations (conceptual change).	*The situated knowledge paradox.* • Referencing incomplete or inaccurate prior knowledge that interferes with new learning (Brickhouse, 1994; Land & Hannafin, 1997); • Making imprecise and unreliable observations of everyday experiences and using them to justify naive theories (Brickhouse, 1994).	*Prompt and guide connections to prior knowledge.* • Use familiar experiences and orienting strategies to prepare learners conceptually (Ausubel, 1963; Cognition and Technology Group at Vanderbilt, 1992; Hannafin & Rieber, 1989; Schwartz, Brophy, Lin, & Bransford, 1999); • Use external models such as diagrams, analogies, metaphors, or adjunct questions to stimulate transfer and conceptual change (Mayer, 1999); • Use modeling and instructor-student conversations to diagnose and guide developing explanations (Petraglia, 1998; Roth, 1995).
Use of resource-rich environments to support learner-centered inquiry	*Generate and refine questions, interpretations, and understanding based on new information.* • Identify and refine questions, topics, or information needs (metacognition); • Monitor the effectiveness of search results and strategies and refine them when unproductive (metacognition; procedural knowledge); • Monitor the fine details of a project or investigation, remaining focused on the "forest" or broader purposes without getting lost in the "trees" (comprehensive monitoring); • Integrate information coherently from a variety of sources (reasoning).	*The metacognitive knowledge dilemma: Monitoring learning in the absence of domain knowledge.* • Failure to refine known strategies when ineffective (Hill & Hannafin, 1997); • Topic knowledge is often incomplete, which hinders deep evaluation and strategic use of information resources (Lyons, Hoffman, Krajcik, & Soloway, 1997); • Epistemological orientations that are counter to those required for effective learning with OELEs (Wallace, Krajcik, & Soloway, 1997; Oliver, 1999).	*Provide explicit scaffolding of metacognition and teaching-learning strategies.* • Embed scaffolds directly into technology interface to prompt and model the reflective process (Bell, 1998; Hmelo & Day, 1999; Lewis, Stern, & Linn, 1993; Lin, Hmelo, Kinzer, & Secules, 1999; Salomon, Globerson, and Guterman, 1989; Scardamalia, Bereiter, McLean, Swallow, & Woodruff, 1989; • Use organizing frameworks to help teachers and learners make strategies and progress explicit (Schwartz et al., 1999).

From these observations, it is expected that theories emerge about the relationship between specific insulation materials and heat flow. Visualization and manipulation tools, then, enable access to, and manipulation of, concepts that would typically be inaccessible to learners, given the complexity of the data set or the "invisible" nature of a process (such as heat flow) (Gordin & Pea, 1995).

Cognitive Requirements: Generate, Test, and Refine Theories, Based on Supporting Evidence Perceived from Visual Displays

Manipulation and visualization tools help learners access, inquire about, and conduct experiments with complex data sets. In order to take advantage of these opportunities, specific cognitive processes are required (refer to Table 1). Through a process of theory building, learners make predictions, design experiments to test them, and use supporting evidence to back up their claims (Land & Hannafin, 1996).

With visualization and manipulation tools, learners must be able to make accurate observations from visual displays and link these observations to plausible explanations. In order to accomplish these processes, learners must perform several cognitive operations such as (but not limited to):

- Recognizing whether changes in a visual display have occurred as a result of manipulating a variable (while holding others constant) (selective perception; cognitive strategies);
- Discerning which visual cues are relevant to attend to in a visual display (discrimination);
- Drawing accurate conclusions from observations of visual cues (i.e, does this cue mean that something has increased, decreased, slowed down, changed directions?) (causal reasoning);
- Relating conclusions to plausible explanations (inferencing; theory building)

To illustrate using the previous thermodynamics example, a learner might manipulate and simulate the effects of wool versus paper material to insulate an object. To generate, test, and refine theories about factors affecting the cooling process, learners must be able to recognize what changes, if any, occurred as a result of the manipulation and what they mean; (i.e., With paper material, how did the cooling process differ in comparison to wool?). Furthermore, learners must be able to attend to the most *salient* visual cues that are predictive. In this instance, the relevant visual cues are the type of insulation material manipulated (wool vs. paper) and the associated graphical representation of temperature (increase, decrease, or no change) over time (start time to end time). In contrast, attending to the *color* of the insulation material is irrelevant, so using it to explain heat flow would not lead to accurate conclusions. Finally, learners must design experiments to test developing theories (e.g., hold variables constant), and evaluate theories based on supporting evidence (What did the experiment tell me related to my theories?).

Problems and Issues: Limitations of Novices to Accurately Perceive and Interpret Visual Cues

Although drawing accurate conclusions from observations is a critical cognitive requirement, prior studies on expertise have shown that novice learners are often marked by perceptual limitations that are likely to impact the precision of their observations. Novices are likely to attend to surface features (Chi, Feltovich, & Glaser, 1981) and to have limited pattern recognition abilities (deGroot, 1965). In the context of OELEs, perceptual problems can lead to biased interpretations or to the reinforcement of naive conceptions that are difficult to detect or rectify (Roth, 1995). Table 1 summarizes problems and issues related to drawing accurate conclusions from visual cues, including the following:

Attending to, and attaching meaning to, irrelevant visual cues. Gyllenhaal and Perry (1998) examined how visitors learned about the seasons from a museum computer exhibit. They found that with one computer simulation, visitors often walked away with misconceptions inadvertently confirmed, in part, because they attended heavily to irrelevant visual cues. Specifically, users confirmed the intuitive conception that summer occurs because the Earth is closer to the sun and winter occurs because the Earth is farther away. Even though the simulation depicted visually the Earth's *tilt* in relation to its distance from the sun and subsequent seasonal changes, learners attended to another, more trivial visual cue: that summer occurs on the hemisphere of the Earth tilted toward the sun that is also *closer to the sun*. Consequently, they continued to attribute causes of seasonal change to the Earth being significantly closer to the sun (and ignored axis tilt as the salient explanatory factor). Despite efforts to make the effects of tilt and orbit more visually apparent, learners continued to misinterpret visual information in favor of their underlying beliefs.

With OELEs, information required to form inferences is often available in a visual format—that is, objects become animated, change color, blink, or otherwise move as a result of learner manipulation. From these observations, learners formulate or refine conjectures, or both. Yet, novice learners tend to confuse visibility with relevance and apply little consideration to the underlying logic of their selection (Petre, 1995). This means that novice learners are often unprepared to judge what information is relevant, and they often do not recognize when their observations are imprecise or irrelevant. This becomes problematic with OELEs because, even though novices may not require precise sources of evidence to make meaning, they nonetheless *use* what they perceive.

Brungardt and Zollman (1995) reported this problem in a study of learners using a microcomputer-based laboratory (MBL) and interactive videodisc to investigate kinematics. They found that learners often selected irrelevant visual cues—mild fluctuations of a graph—and used them to explain conceptual relationships. They noted, ". . . many students tended to consider every bump on a graph to be significant, ignoring the fact that irregularities in the graphs are often due to many error sources" (p. 866). Consequently, learners both attended to and attached meaning to these fluctuations, believing that they indicated a momentary change (slowing down) in speed. In instances where trivial visual cues are selected as relevant, misleading explanations can result that become difficult to further test or refine.

Drawing inaccurate conclusions from visual cues. In discussing how inaccurate perceptions can lead to inaccurate conclusions, Rieber (1995) details a story of Percival Lowell, a prominent astronomer at the turn of the century, who reported long crossing lines on the martian landscape. Lowell concluded from these observations that the lines were the remnants of canals constructed by an ancient civilization. Unfortunately, his perceptions (and consequently, his conclusions) were inaccurate; the canals turned out to be optical illusions. Likewise, student misperceptions of visual cues can lead to inaccurate conclusions that affect theory development.

Land and Hannafin (1997), for instance, studied learners using *ErgoMotion*—a computer-based microworld that supports exploration of force and motion through design of a virtual roller coaster. With *ErgoMotion*, students alter design variables, such as curve radius, coaster mass, hill size, and engine horsepower, and then simulate the results, viewing video simulations of the outcomes (coaster functioning, crashing, or failing to ascend hills). Findings suggested that seventh graders relied heavily on video simulations of the roller coaster to judge relative differences in the coaster's speed; that is, they formed conclusions about changes in speed based solely on whether the coaster "looked" as if it went faster or slower than on a previous trial. Yet, with *ErgoMotion*, judging precise differences in speed was not possible using video animations alone. Consequently, learners often misinterpreted the video displays to mean that the coaster was speeding up or slowing down when in fact no change in speed occurred.

Making biased observations of visual cues based on preconceptions. In the case of *ErgoMotion*, errors in interpretation about speed were problematic because they were used to confirm an intuitive (and inaccurate) theory that engine horsepower influences acceleration. That is, learners intuitively believed that decreasing engine horsepower would decrease velocity. So when they wanted to decrease coaster speed, they would typically decrease engine horsepower and simulate the model. However, when no change in velocity occurred, learners would nonetheless confirm their theory that it decreased, claiming that the coaster looked like it went slower.

These findings, among others, give credence to the notion that preconceptions influence and often bias observations (Chinn & Brewer, 1993; de Jong & van Joolingen, 1998). To the extent that critical feedback is represented ambiguously with OELEs, misperceptions become a cause for concern—particularly because learners are more likely to use ambiguity to protect, rather than question, naive beliefs (Karmiloff-Smith & Inhelder, 1975). Misperceptions of this nature can be very difficult for teachers to detect, making it possible for learners to construct meaningful, but erroneous, conclusions that are robust and persistent.

Implications for Design: Direct Learner Attention to Key Variables and Visual Cues

Table 1 provides a summary of design implications aimed at reducing the likelihood of learner misperceptions and misinterpretations of visual information.

Accentuate critical variables visually. Creating displays that visually highlight or constrain key variables may help learners attend to important visual cues. Strategies such as reducing the richness of visual displays can help novices attend to relevant features (Petre, 1995). This can occur by reducing both the number and complexity of visual cues available (e.g., using line art instead of high fidelity images) or by using techniques to highlight and constrain key variables (e.g., using color, flashing, or "zooming" to amplify) (Hamel & Ryan-Jones, 1997; Hannafin & Peck, 1988). Visual representations of information should be designed to make data sets coherent and to encourage learners to attend to and compare critical aspects (Tufte, 1983).

Enhance more objective comparison of different visual displays. Roth (1995) reported several effective strategies to help learners attend to relevant visual cues in the *Interactive Physics* microworld. These strategies were based on a juxtaposition of images designed to highlight crucial aspects of the simulation in order to help learners attend to them. To make these features more clearly visible to learners, use of the following strategies was incorporated: (a) repeated animated motions in real-time and slow-motion or step-wise changes; and (b) direct visual comparison of differences between two parallel events. Others have used similar strategies successfully where the simulated results of a real-time experiment were plotted and superimposed on a graph of the students' predictions (Lewis et al., 1993). Juxtaposing new and prior outcomes, or actual and expected values, may help to amplify the meaning of a visual display more objectively (Roth, 1995), and may help learners better attend to distinctions between two different events or models.

Similarly, with *The Progress Portfolio* (Loh et al., 1997), students are supported to highlight comparisons of two or more pieces of evidence. Learners can take "snapshots" of graphs or images and align them side-by-side in "evidence fields" within their portfolio. They can then look for similarities and differences, drawing arrows to point out specific features and using "sticky" notes (similar to electronic *Post-It*™ notes) to explain what they see. Within evidence pages, students draw conclusions about the evidence compared. Such strategies not only help learners attend to visual distinctions, but they also offer a way for learners to articulate their perceptions and interpretations in ways that can be visible to, and monitored by, teachers.

Provide explicit support for learners to interpret the meaning of visual representations. One reason learners have difficulty selecting and interpreting visual cues is that they lack familiarity with the way data is represented (i.e., determining what specific colors, graphs, or units such as Kg, meter, and MHz mean) (Gordin, Edelson, & Pea, 1996). Providing explicit support for learners to make connections between new representations and familiar referents is an important strategy to help novices with little prior knowledge construct interpretations. For instance, Gordin et al., (1996) asked middle school students, prior to using a weather visualization tool, to explore the relationship between colors and data values by making maps (using crayons and paper) of their own scientific visualizations. Subsequently, this helped them to interpret more complex representations with the visualization tool.

It may also be useful to design computer interfaces using graphical metaphors to help learners make connections to familiar situations, although more research is needed to support this claim (Rieber, Noah, & Nolan, 1998). This could involve simplifying visual displays to represent information in more intuitive ways. For instance an object's density could be represented by superimposing a series of either widely spread or tightly packed dots on the object, rather than displaying numerical representations. Foley (1998) successfully used a "dot density" technique to represent the process of heat flow by increasing or decreasing the density of dots around an object that was cooling. Representing information metaphorically may help give learners a context for reasoning with data and make complex representations more accessible (Tufte, 1983). Combinations of elaborated text, graphics, and numbers may also aid learners to direct attention to important information, compare data, and interpret feedback (Rieber, Tzeng, Tribble, & Chu, 1996; Tufte, 1983).

Use modeling, dialogue, or both to help learners attend to and interpret complex visual representations. In some instances, maintaining the complexity and authenticity of visualization tools is desirable—even for novice learners. For instance, the *CoVIS* (Pea, 1993) and *Kids as Global Scientists* (Lee & Songer, 1998) projects encourage students to access the same weather visualization tools used by meteorologists for weather prediction. This is believed to help students learn science authentically. Yet, students who lack prior domain knowledge are also likely to lack perceptual precision needed to distinguish relevant trends and patterns. This might make it difficult for novices to select relevant visual cues and to interpret what they mean. Assisting learners in making connections between representations and meanings while they are simultaneously learning these representations and meanings is a difficult design dilemma that may require extensive support and modeling.

Gordin et al., 1995, provide a good example of supporting novices to interpret complex visual representations (with the CoVIS weather visualization tool). They expected that children would have difficulty attending to the important visual relationships rendered by the tool, because of limited prior knowledge and familiarity. Consequently, a question and answer pattern was established to help learners attend to the significant relationships that were represented visually (e.g., extremes, correlations, or inverse correlations among color values). Through asking questions that amplified these relationships on the screen, the teacher successfully helped learners recognize the importance of looking for anomalies and how they were represented visually. Students were then questioned to form hypotheses about what was causing the anomalies. If necessary, the teacher would then help the students design experiments to test their hypotheses using the visualization tool. Through instructor guidance and ongoing assessment of student understanding, teachers helped learners extend current understanding and internalize new ways of learning and "doing" science.

Use of Authentic Contexts to Foster Connections Between Formal Knowledge and Everyday Experience

Recent trends in learning emphasize the situated nature of knowledge and the impact that contexts, tools, and social interaction have on understanding (Brown, Collins, & Duguid, 1989; Cobb & Bowers, 1999). Instruction that is anchored in complex, holistic contexts presumably supports learners to consider why, when, and how knowledge can be applied meaningfully (Cognition and Technology Group at Vanderbilt [CTGV], 1992). OELEs use problem contexts that immerse learners in authentic activities of realistic complexity (e.g., learn ecology by resolving water pollution problems; learn meteorology by predicting weather patterns) in order to help learners ground interpretations in everyday experience. Making connections to out-of-school contexts guides students to integrate formal and life experiences and to develop meaningful, long-lasting understandings (Brickhouse, 1994).

Cognitive Requirements: Integrate New and Prior Knowledge

In complex, authentic environments, learners often enter the learning experience with little related domain knowledge. Furthermore, learning tasks often involve considerable complexity, where multiple disciplines are crossed and knowledge is incomplete in one or more domains. In order to meet the demands of a complex learning environment, learners must draw on prior experiences to organize new knowledge. They must bring to bear established knowledge to interpret new situations where domain knowledge is lacking (Brown, Bransford, Ferrara, & Campione, 1983).

Specific cognitive requirements for learners to integrate new and prior knowledge with OELEs are summarized in Table 1 and include:

- Making voluntary references to examples, analogies, metaphors, prior knowledge, or personal experience to map new, classroom knowledge onto natural, everyday events (transfer; analogical reasoning);
- Evolving initial, naive conceptions and explanations (conceptual change).

Problems and Issues: The Situated Knowledge Paradox

With OELEs, making connections to prior knowledge is needed to meaningfully integrate new knowledge and to enhance the potential for transfer. Although links to prior knowledge in everyday contexts may enhance the potential for transfer (Brown et al., 1983), they also increase the likelihood that learners may draw on incomplete or inaccurate understanding, which forms the basis of faulty theories. Table 1 summarizes some of the problems experienced by learners to make connections to prior knowledge in open-ended, authentic contexts.

Referencing incomplete or inaccurate prior knowledge that interferes with new learning. It is well documented that learners often have prior experiences or intuitive conceptions that may be contradictory to formal, accepted explanations (Carey, 1986; Champagne, Gunstone, & Klopfer, 1985). Novices organize knowledge differently than experts because they lack domain-specific knowledge needed to coordinate patterns in memory that can be brought to bear during new learning (deGroot, 1965). Although naive conceptions may be important for formulating initial explanations of a problem, evolving them is often more problematic (Strike & Posner, 1992).

To illustrate, with the *ErgoMotion* roller coaster environment, some learners referenced prior knowledge and experiences that contradicted, or interfered with, the scientific treatment of force and motion (Land & Hannafin, 1997). For instance, if the coaster crashed around a curve, learners often attempted to decrease coaster speed by reducing engine horsepower, associating this action to the application of brakes on a bicycle to navigate a curve. Yet, this theory from everyday experience did not easily correspond to the microworld experience and was inconsistent with accepted scientific views. In another instance, a learner referred to the regulating effects of a computer on the speed of the coaster, and the use of brakes and "clamps" for stopping the coaster. She recalled a roller coaster operator telling her that such devices could be used to stop the coaster in the event of an emergency. Consequently, she continued to make references to brakes and clamps when addressing issues of slowing down and stopping. Learner intuitive theories that are connected to everyday experience are extremely resistant to change. Without repeated opportunities to disconfirm or to question the limitations of intuitive theories, learners strengthen powerful generalizations that are not readily transferable.

Making imprecise and unreliable observations of everyday experiences and using them to justify naive theories. Despite the theoretical ideals of transfer, novice learners do not always make connections to prior knowledge or everyday experiences in ways that are productive for learning. To illustrate, Brickhouse (1994) studied how children linked school-related concepts of light and shadow with everyday experiences at home. She found that students *did* link classroom and everyday experiences, yet their observations outside of the classroom were unreliable and unpredictable. Students often inaccurately remembered events and failed to perceive critical details of their experiences. Furthermore, their partial understanding of light could not be easily *disconfirmed* given the imprecise nature of their observations, so they often used it to justify a naive theory.

In contrast, during classroom observations of light where the teacher directed and constrained student investigations, students developed simple scientific ideas and recognized when evidence confirmed or refuted their theories. Brickhouse (1994) explains the findings:

> Because their experiences with light outside the classroom were not constrained in the same way as they were in classroom experiments, they reported observations that their developing theory could not yet explain. The investigations in class were designed to be as unambiguous as possible. This approach had an advantage in that students all collected the same data and the teacher knew in advance what the data ought to look like . . . However, in everyday contexts, the children did not see the isolated effect of a single variable . . . . The situated knowledge of this classroom, although largely useful in that context, was less useful for explaining the complexities of everyday life (p. 651).

Thus although learners developed theories of light that were useful in the constrained classroom context, they were isolated from, and did not transfer to, everyday contexts.

These findings point to a *situated knowledge paradox* involving an apparent trade-off between constraining and situating learning. Constraining in-class investigations may support learning in ways that can be more predictably monitored and shaped to match a novice learner's partially developed understanding. Given that novices are marked by undeveloped knowledge structures (Gick, 1986), engaging in effective theory building in everyday contexts, wherein knowledge resides both more naturally and complexly, may be overly optimistic and, at times, counterproductive. Novices lacking coherent knowledge structures may misapply prior experiences or use observations to unknowingly strengthen naive theories. Where misconceptions are involved, the effect is further intensified in that prior knowledge and experience are exceptionally robust. However, relying exclusively on classroom contexts where investigations are constrained and ambiguity is reduced may lead to development of knowledge that is not transferable and limited only to school contexts (Brickhouse, 1994). Although the benefits of building upon meaningful experiences within situated environments are clear, the pedagogical challenges associated with effectively realizing them remain formidable.

Implications for Design: Prompt-and-Guide Connections to Prior Knowledge

The previous section pointed to a need for designs that assist learners in both accessing and expanding prior knowledge in absence of domain knowledge and strategies. Table 1 summarizes design implications for helping learners make connections to prior knowledge.

Use familiar experiences and orienting strategies to prepare learners conceptually. A common technique to help ground learner interpretations in absence of prior domain knowledge is to use orienting strategies that prepare learners to think about concepts in a familiar way (Hannafin & Rieber, 1989). This is often accomplished with "advance organizers" (Ausubel, 1963) or background scenarios that help learners connect real-world problems to the classroom (CTGV, 1992). The framework of "anchored instruction" emphasizes use of highly contextual and familiar experiences to anchor learning, relying on video-based stories or challenges to orient learners to the task at hand (see for instance, Jasper Woodbury Series [CTGV, 1992] and the STAR.legacy project [Schwartz, Brophy, Lin, & Bransford, 1999]). By using real-life stories and challenges, learners are not only prepared conceptually for learning but also are guided to discover relevance and interest in the topic.

Use external models such as diagrams, analogies, metaphors, or adjunct questions to stimulate transfer and conceptual change. Given that novice learners often hold naive conceptions that are intuitive and unspoken, it is not surprising that they experience great difficulty in improving them independently (Perkins & Unger, 1999). Consequently, some researchers have successfully used external models such as analogies, metaphors, adjunct questions, or pictorial representations (e.g., Mayer, 1999) to prompt learners to make connections and to reorganize current ideas. When external support mechanisms emphasize ideas that learners typically confuse or fail to realize independently, they are more likely to stimulate productive analogical reasoning (Linn, Shear, Bell, & Slotta, 1999; Vosniadou & Ortony, 1989). Linn et al. (1999) note that, with thermodynamics, students often hold naive beliefs that metals impart cold temperatures, associating this idea with the "feel" of metal at room temperature; furthermore, these notions often interfere with instructional treatments. To respond to these conflicting beliefs, Linn et al. (1999) suggest using what they call "pivotal ideas" to help students make connections to everyday experiences that are more productive for learning:

> If we ask students to explain how metals feel in a car on a hot day, we sometimes stimulate them to compare how metals feel at room temperature to how metals feel in warmer situations. This idea motivates some students to reorganize their ideas about materials, distinguishing conductors from insulators . . . [Thus], introducing a hot automobile trunk (or hot oven) is *pivotal* because it motivates a reorganization of ideas. (p. 64).

Hence, Linn et al. (1999) highlight the importance of using analogies to stimulate not solely connections to prior knowledge, but also connections that serve to *reorganize* prior knowledge that might potentially interfere with learning.

Use modeling and instructor-student conversations to diagnose and guide developing explanations. Recognition of typical problems experienced by learners with little prior knowledge can help guide teachers to the types of pivotal questions and conversations to pursue. Some researchers have used a combination of external questions, technology use, and collaborative dialogue to help learners develop shared understanding (Bell, 1998; Hmelo & Day, 1999). Roth (1995), for instance, used conversations with students using *Interactive Physics* to prompt and guide connections to related, everyday experiences. Given the limitations of technology to "understand" and adapt to student needs, student-teacher conversations may play an important role in helping learners with little domain knowledge proceed from a point of mutual understanding, rather than misunderstanding.

The significance of dialogue during complex learning is longstanding and is often illustrated with Palincsar & Brown's (1984) work on reciprocal teaching. Their approach relies on teacher modeling and dialogue to guide students to learn reading comprehension strategies both independently and with each other. Likewise, Petraglia (1998, p.63) argues for the use of teacher-student dialogue during learning with educational technologies (citing the work of Driver et al., 1994):

> If students are to adopt scientific ways of knowing, then intervention and negotiation with an authority, usually the teacher, is essential. Here, the critical feature is the nature of the dialogic process. The role of the authority figure has two important components. The first is to introduce new ideas or cultural tools where necessary and to provide the support and guidance for students to make sense of these for themselves. The other is to listen and diagnose the ways in which the instructional activities are being interpreted to inform further action . . . . (p. 11)

Thus use of teacher-student, and perhaps student-student, conversations may play a critical role in facilitating the development of understanding with OELEs.

The diagnostic aspect of teacher-student dialogue may be significant for learning with OELEs. By engaging students in conversations, teachers can guide and assess understanding about important concepts, and redirect them if necessary. Roth (1995) summarized his approach to using teacher-student conversations during learning with the *Interactive Physics* microworld to provide adaptive support:

> First, I needed to assess students' learning—that is, to identify their ways of seeing and talking about the microworld phenomena . . . . To assess student progress, I had to engage them in a conversation in which they could explicate their present understandings . . . . If the probe was positive—that is, students' science talk was appropriate—I could move on to another group. However, if the students' discourse was inappropriate . . . I had to take some action to help students along a trajectory toward more canonical ways of seeing and talking about the microworld. (p. 334)

Conversational interactions with a teacher, then, can reveal critical snapshots into learner enroute perceptions, strategies, and interpretations. Such interactions may be necessary to guide learning effectively and to respond adaptively to the unique sense-making efforts of learners.

Use of Resource-Rich Environments to Support Learner-Centered Inquiry

OELEs often make extensive use of information-rich or resource-rich environments that expand the types of inquiry possible (Hill, 1999). Using information retrieval systems such as the World Wide Web (WWW), students browse vast information resources on topics such as weather, ecology, or population statistics, and use these resources to investigate open-ended problems (Rakes, 1996). In concert with supporting resources, learners formulate questions for investigation, design plans, or create artifacts (such as WWW portfolios; multimedia presentations; design documents) that represent their understanding (Blumenfeld et al., 1991). By generating goals and questions for inquiry, learners are empowered to develop their own interests and are more likely to be motivated and mindful about learning (Salomon, 1986). Resource-rich environments, such as information technologies, CD-ROMs, or databases, make extended inquiry possible by increasing the availability and variety of information on a topic (Rakes, 1996).

Cognitive Requirements: Generating and Refining Questions, Interpretations, and Understanding Based on New Information

With OELEs, learners are responsible for directing and monitoring the learning process; they generate and refine understanding as new information is evaluated in light of current theories, problems, questions, or knowledge gaps (Land & Hannafin, 1996). The process of formulating questions, identifying information needs, locating relevant information resources, and coordinating theories and evidence forms the foundation for critical thinking skills necessary for learning with resource-rich environments (Rakes, 1996). Kuhn (1999) argues that developing competencies for critical thinking depends primarily on metacognitive rather than cognitive competencies. When learning with resource-rich environments, metacognitive knowledge is essential to identify gaps in understanding, evaluate information in light of identified needs, reflect on the effectiveness of the search process, and refine known strategies when unproductive (Hill & Hannafin, 1997; Moore, 1995).

Metacognition is often described as consisting of three interrelated elements: (a) knowledge-related awareness of what one knows, how one knows it, and whether cognitive efforts are successful; (b) task-related awareness of cognitive demands; and (c) procedure-related awareness of how to select and use cognitive strategies and how to monitor and revise these strategies when necessary (Garner & Alexander, 1989; Kuhn, 1999; Moore, 1995). Table 1 provides a summary of cognitive requirements for learning with resource-rich environments, including:

- Identifying and refining questions, topics, or information needs (metacognition);
- Monitoring the effectiveness of search results and strategies and refining them when unproductive (metacognition; procedural knowledge);
- Monitoring the fine details of a project or investigation, remaining focused on the forest or broader purposes without getting lost in the trees (comprehension monitoring);
- Integrating information coherently from a variety of sources (reasoning).

Problem and Issues

The metacognitive knowledge dilemma: Monitoring learning in the absence of domain knowledge. Learning in resource-rich OELEs requires metacognitive awareness of what is known, and what needs to be known, about a given topic. Yet metacognitive strategy use is often dependent on prior domain knowledge (Garner & Alexander, 1989; Greene, 1995) and system knowledge with information retrieval systems (Hill & Hannafin, 1997). The complex relationship between prior, system, and metacognitive knowledge is likely to surface during learner interaction with resource-rich environments, given the lack of external structure and the breadth and depth of a vast resource base. Specific problems and issues associated with learning in resource-rich OELEs are summarized in Table 1.

Failure to refine known strategies when ineffective. One problem experienced by learners in resource-rich environments such as the WWW involves monitoring and refining search terms and strategies. Prior studies have shown that many learners fail to alter unproductive search strategies, even when they are aware of their limitations (Hill & Hannafin, 1997), and they often search through numerous information resources in absence of an organizing context, question, or goal (Land & Greene, 2000). Metacognition is critical to helping learners limit the search space, filter relevant from irrelevant information, and effectively coordinate questions and supporting information (Moore, 1995). Without metacognition, students can become overwhelmed in determining what information is relevant to their needs and what they need to do to refine known strategies.

Yet refining search terms is also dependent on having some knowledge of the topic or domain (Hill & Hannafin, 1997). As reported by Moore (1995), the "generation of alternative search terms may not be an option when little is known of the topic, nor was it an option [in her study] for the three students who interpreted search term absence as an indication that the library had no information on the subject" (p. 13). In instances where students fail to refine search strategies when initial efforts are unsuccessful, they are more likely to abandon their efforts, experience considerable frustration, or reveal persistent fragmentation of understanding (Land & Greene, 2000).

Topic knowledge is often incomplete, which hinders deep evaluation and strategic use of information resources. Effective inquiry with information technologies is heavily dependent on learners' asking questions that are focused and amenable to investigation (Wallace, Krajcik, & Soloway, 1997). Generating questions that are either too broad or too narrow will probably result in failure to deepen understanding. Some topic and metacognitive knowledge seem necessary to generate effective questions and search terms and to continually monitor the fit between "local" information with more global questions (Hill & Hannafin, 1997; Land & Greene, 2000). It is often presumed that learners will be able to "spontaneously mobilize prior knowledge to generate questions on a little-known subject" (Moore, 1995, p. 10). Yet assessing what is known in order to identify gaps in knowledge is a metacognitive process that is often difficult for novice learners to perform independently (Salomon, 1986).

Lyons, Hoffman, Krajcik, & Soloway, (1997) found that middle school children using the WWW for science inquiry often failed to generate questions that were focused enough to be informed by information resources. They reported:

> Students often employ a method that can best be described as "question drift." That is, students will ask a somewhat general question, and then focus it by finding information on-line that had something to do with their topic. If they could not find information to match the original direction of their question, then they would change directions, or sometimes even whole topic areas. (p. 14)

Question drift seems connected to problems in both identifying focused questions for investigation and in refining strategies when initial efforts are ineffective. In absence of good driving questions informed by some topic knowledge, learners have difficulty managing the complexity of searching through numerous information resources and using them to deepen understanding.

OELEs are designed to be complex, and they require learners to generate questions and to maneuver within a resource-rich environment, even when background knowledge is incomplete. Hence students are often left to discover and infer how various resources might be useful. Yet it is unlikely that novices with low topic knowledge will "discover" the usefulness of resources independently (Greene & Land, in press). Finding ways to help learners constrain and focus their inquiries, without overly prescribing them a priori, is an important design issue for learning with resource-rich OELEs.

Epistemological orientations that are counter to those required for effective learning with OELEs. A related problem in learning with OELEs involves the mediating role of epistemological beliefs on learning (Oliver, 1999) and possible developmental limitations for critical thinking by young children (Kuhn, 1999). Some learners hold epistemological orientations that are inconsistent with constructivist values—such as a belief that knowledge is acquired through transmission of the "truth" from an authority figure (Kitchener & King, 1981). Although the norm among children, adults can also experience difficulty with more constructivist orientations toward learning (Kuhn, 1999). When nonconstructivist epistemologies are brought to bear during learning with OELEs, learners quickly can become frustrated in their (unsuccessful) efforts to learn and verify the correct "answers."

To illustrate, Wallace and Kupperman (1997) found that middle school students often applied a strategy of "finding the answer" during inquiry with the WWW. Learners tended to view the goals of the activity as finding an answer to their research question, and "thus reduced the task to finding a single page, the perfect source, on which the answer could be found" (p. 13). The goal of these approaches was to submit search after search until the smallest amount of hits was returned. The following type of interaction reflects this approach:

> One pair of students . . . reacted effusively to small hit lists, singing and calling out "yes, we got it now . . . hey you guys, we got it!" when they saw that the number of hits from a search was 18, then reacting with equivalent disappointment when a cursory viewing of the hit list did not reveal an obviously appropriate site: "All these things stink . . . cause we put in *animals* . . . let's delete *animals*." Later, these students produced a hit list with only three pages, and . . . exclaimed, "Oh my gosh, we got it!"

Oliver (1999) noted similar findings where middle school students seemed oriented to find the answer to questions that were available through the *KIE Mildred* tool to guide them during learning. The teacher commented on this technique noting that ". . . they're not going deep enough, they are just pulling one little answer and stopping . . ." (p. 14).

In these instances, learners seemed to rely on orientations that were not inherently supported by OELE designs, tools, or resources. Developing epistemological orientations that are more evaluative and conducive to the uncertainty associated with learning with OELEs may be an important consideration in implementation—particularly since learners and teachers may be more familiar with traditional, materials-driven and teacher-centered approaches. Repeated learning experiences with OELEs may be necessary before learners can apply appropriate strategies and epistemologies.

Implications for Design: Provide Explicit Scaffolding of Metacognition and Teaching-Learning Strategies

Learning in open environments often involves working on multiple activities, analyzing diverse perspectives and resources, testing ideas through experimentation, and integrating varied components into a coherent whole. In essence, thinking and doing are complementary, as reflection and action continually inform each other (Schön, 1983). Managing this process on a metalevel can be challenging for learners with little prior knowledge and little experience with the complexity of inquiry (Schwartz et al., 1999). Table 1 summarizes implications for supporting learner metacognition during learning with OELEs.

Embed scaffolds directly into technology interface to prompt and model the reflective process. Salomon, Globerson, and Guterman (1989) extended Palincsar and Brown's (1984) work with dialogue and reading comprehension strategies to consider the functions of computer technology to afford similar guidance. They argue that three basic elements of effective, guided social interactions can also be found in computer-learner partnerships: (a) the provision of an explicit model by a more capable peer during interaction; (b) the "activation of mental operations that the learner would have difficulty using without that partnership" (p. 621); and (c) the use of appropriate metacognitive guidance. They state, however, that most computer-learner partnerships fail to meet the third criteria: provision of explicit metacognitive guidance.

One strategy for providing metacognitive guidance involves embedding support, or scaffolds, for procedural, strategic, or metacognitive control. Scaffolds for self-regulation can be embedded directly into the technology interface to encourage reflection and to help learners focus on important aspects of the learning task (Lin, Hmelo, Kinzer, & Secules, 1999; Scardamalia, Bereiter, McLean, Swallow, & Woodruff, 1989). Embedded scaffolds can range from use of questions to help guide learner investigations with simulations (de Jong & van Joolingen, 1998; Hmelo & Day, 1999) to reminders or suggestions for metacognitive reflection on reading or writing activities (e.g., Salomon et al., 1989) to use of pull-down menus that require learners to label and make overt their thinking (Scardamalia et al., 1989). Others have embedded prompts for learners to make predictions and then to connect those predictions to observations (Lewis et al., 1993) and to organize scientific arguments according to theories and evidence (Bell, 1998).

Some caution is needed against relying solely on the use of embedded support for metacognition with OELEs. Some studies indicate that learners do not always benefit from their use (Greene & Land, in press; Oliver, 1999). The value of such support is largely dependent on the extent to which learners both recognize the need for it and actually use it. It is not uncommon for learners to ignore suggested strategies or questions, believing that the guidance is unnecessary or a hindrance to progress. Also, as learner-control studies frequently illustrate, learners may not be aware that they require assistance or that they are approaching a task unproductively (Steinberg, 1989). Embedded support mechanisms can help direct learners to productive strategies or interpretations, but are insufficient to diagnose how well learning is progressing or what type of support is needed. In addition to teacher-student interactions, it may also be necessary to incorporate artificial intelligence functions that monitor and summarize the actions taken by learners (Lajoie, 1993) or provide advice-based discrepancies between student and expert choices (Suthers, Toth, & Weiner, 1997).

Use organizing frameworks to help teachers and learners make strategies and progress explicit. Recent efforts emphasize a "systems approach" to supporting reflection that coordinates multiple guidance mechanisms—some that are embedded into the technology and some that are provided through dialogue among peers and teachers (Lin et al., 1999). The STAR.legacy project by the Cognition and Technology Group at Vanderbilt (Schwartz et al., 1999) is a software shell designed to make the iterative nature of the inquiry process explicit to both teachers and learners. The model is based on progressive increases in complexity and support for articulation and revision of ideas. Dialogue and sharing with peers and teachers are built into the model at appropriate points during the inquiry process. Using STAR.legacy as an organizing framework, learners are supported to generate initial ideas, consider additional perspectives, research their ideas, revise ideas based on reanalysis and feedback, and post designs for public review.

The role of the "master teacher" in orchestrating learning with OELEs should not be understated. Well-known teaching frameworks such as the *conceptual change model* and the *KWL* (know, want, learn) model have been used by teachers to support the tentative and evolving nature of student-centered learning. For instance, the conceptual change model (Stepans, 1996; Strike & Posner, 1992) promotes discussions and activities for students to articulate initial preconceptions, confront them through use of conflict strategies, and resolve them based on awareness of discrepancies. The KWL model (see, for example, Jared & Jared, 1997), is a reading comprehension framework that is used to make explicit what students *know* about a topic (K), what they *want* to know about (W), and what they have *learned* (L). Often posted on walls around the classroom, such frameworks become a natural part of the inquiry process, structuring classroom activities, demonstrations, and discourse. Integrating OELEs with powerful teaching frameworks that make the iterative knowledge-building process explicit is a compelling area of future classroom-based research.

CONCLUSION

This paper raised issues surrounding how learners perceive and interpret phenomena during learning with OELEs. When constructing meaning with OELEs, where little explicit direction is provided, misperceptions, misinterpretations, or ineffective strategy use may follow. Such issues can lead to significant misunderstandings that are difficult to detect or repair. When learners have little prior knowledge of a topic and are immersed in a learn-by-doing environment, a bootstrapping dilemma exists where some metacognitive and prior knowledge are needed to ask good questions and to make sense out of the data and events being modeled. As Salomon (1986) recognized, when learning environments are designed to support thinking-intensive interactions, successful learning becomes highly dependent on learner voluntary cognitive engagement. Yet these psychological operations are not likely to be realized spontaneously without external support (Salomon, 1986). To improve the effectiveness of OELE designs, strategies are needed to help learners attend to important information, construct coherent explanations, and self-regulate when they have little background knowledge.

Technology has enabled us to consider remarkably new environments and ways of representing information that have been heretofore impossible. In order to seize the potential of these technological innovations, however, explicit attention to learner guidance is in order. As Palincsar (1998) recently suggested, more research is needed on how varied scaffolding methods can be incorporated into learning environments to help learners manage the complexity of student-centered learning. It is hoped that by identifying various problems that learners experience cognitively with OELEs, teachers and designers can be directed to consider more holistic interactions that are important to guide understanding within both socially and technologically rich contexts. ☐

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The author would like to acknowledge Michael J. Hannafin, University of Georgia, and Barbara A. Greene, University of Oklahoma, for their comments on earlier versions of this manuscript. A version of this article entitled "Learning in Open-Ended Environments: Problems and Issues" was presented with Michael Hannafin at the 1998 AECT Convention, Houston, TX.

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