

Hinesley, G.A. (2007). E-learning today: A review of research on hypertext comprehension. *AACE Journal*, 15(3), 255-265.

E-Learning Today: A Review of Research on Hypertext Comprehension

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Use of hypertext is pervasive in education today—it is used for all online course delivery as well as many stand-alone delivery methods such as educational computer software and compact discs (CDs). This article will review Kintsch's Construction-Integration and Anderson's Adaptive Control of Thought-Rational (ACT-R) cognitive architectures and examine how each explains the empirical evidence of comprehension problems related to the use of hypertext systems. This article also discusses design tools based on those two architectures (Cognitive Walkthrough for the Web [CWW] and Scent-Based Navigation and Information Foraging in the ACT [SNIF-ACT] respectively) that can help educational content developers screen their hypertext products for possible comprehension problems prior to its release.

As more and more course material is delivered in distance learning, it becomes of increasing importance to deploy course material that can be used with little or no formal training with the user interface. Currently, over 84% of 4-year colleges and universities in the United States offer distance courses, most of which are delivered online (U.S. Senate, 2002). In addition to postsecondary education, many rural high schools are beginning to use online courses as a means of supplementing their course offerings. It is likely this trend will continue downward through the educational system, with middle and elementary schools engaging in online instruction as well. This will be especially true of small, rural schools struggling with declining enrollments and finding it difficult to afford, or even find, qualified teachers.

Demographics show online college students are more likely to be older, married, and employed than their traditional college counterparts (U.S. Senat, 2002). While one might argue that the typical online college student is mature and motivated enough to make up for any disparities in the online delivery, one would be hard pressed to argue similarly for the online high school, let alone the elementary student. As online course delivery continues to move to lower and lower grades, it becomes increasingly critical we bring all our scientific knowledge to bear to insure the online courses will be of the best quality and delivered in the most appropriate manner for each age group.

Keegan (2001) has noted that distance learning across nations tends to cluster around two poles: group-based and individual-based. Distance learning designed for groups tends to use different technology and pedagogy: the most prevalent being the telecast lecture with interactive capability at the distance sites. There are a wide variety of distance learning venues for the individual: ranging from the correspondence courses in which the student is sent a textbook or other print materials to web-based delivery systems in which the student receives all his/her material from the course website in hypertext format. This article will concentrate of this last delivery method: the pure hypertext format.

The interactive telecast lecture venue used for group distance learning has the advantage of making possible a great deal of social support to the student: if the student is confused about something presented, he/she can question the instructor or another student. Many educators, however, see the teacher-directed nature of the lecture format as a major disadvantage. The constructivist viewpoint of learning holds that students gain more information and cognitive skill through discovery learning. Discovery learning is a student-centered approach to education that allows the learner to explore the world of learning at his/her own pace and in his/her own way. According to the constructivist view point, unstructured hypertext is an ideal delivery system for distance learning because of its flexibility (Malone, 1981). In an unstructured hypertext system, a student can follow any link that piques his/her curiosity, so that no two students progress through the material in the same way or at the same pace (Nielsen, 1990).

In a distance learning setting, with its lack of social support, one needs to be concerned with the consequences of the students' unfettered exploration through the hypertext space:

- How do we prevent them from becoming “lost in hyperspace” (Otter & Johnson, 2000)?
- How do we make certain they understand what they have read?
- How can we make the hypertext delivery system even more responsive to individual learner differences?

These are questions that can be translated into the basic cognitive psychology issues of problem solving and comprehension. Cognitive psychology has a great deal of research addressing these very issues. This article will review current tools being used in research that are based on theories in the field of cognitive psychology and will help educational content developers screen their hypertext products for usability and comprehension prior to its release.

In his paper, “Spanning Seven Orders of Magnitude: A Challenge for Cognitive Modeling,” John Anderson (2002) pointed out that “Much of cognitive psychology focuses on effects measured in tens of milliseconds while significant educational outcomes take tens of hours to achieve (p. 85).” Anderson makes a convincing argument that cognitive modeling is one viable method of bridging the gap spanning Newell’s Cognitive (the actions measured in tens of milliseconds) and Social (actions, such as education, that take months to accomplish) Bands. Thus, this article will largely be confined to cognitive models based on solid cognitive theory and research—models based on Kintsch’s Construction-Integration (C-I) theory, Landauer’s Latent Semantic Analysis (LSA), and models based on Anderson’s ACT-R cognitive architecture.

COGNITIVE ARCHITECTURES

The development and refinement of cognitive architectures has had a strong positive impact of the fields of psychology, education, and human-computer interaction (HCI). According to Byrne (2003), “A cognitive architecture is a broad theory of human cognition based on a wide selection of human experimental data, and implemented as a running computer simulation program” (p. 97). Cognitive architectures are important to the field of psychology because they are integrative—they draw on the learning, memory, problem solving, decision-making, attention, and perceptual-motor literature (Anderson et al., 2003; Byrne, 2003).

This article will abide by the current distinction found in the literature between an *architecture* and a *model* (Byrne, 2003; W. Gray, Young, & Kirschenbaum, 1997; W. D. Gray & Altmann, 2002; Sohn & Doane, 2002). *Architecture* will be used to refer to the theory-based structure that captures a broad range of human behavior in a computer program. A *model*, on the other hand, represents a particular instantiation of the architecture in a confined situation. Both of the cognitive architectures examined are based on a solid base of research and theory; all have useful applications in the educational field while continuing to add to our understanding of basic cognition. I will be using these cognitive architectures, and the models based on them, to show not only how they can be used to predict the problems found in navigation and comprehension of hypertext, but also how they can be used as design tools to help avoid the problems. Let me start by briefly describing the two architectures.

C-I and LSA

The construction-integration (C-I) theory was originally developed by Kintsch to account for how readers can arrive at the correct meaning of a word with multiple meanings (such as the word *bank*) when reading a passage (Kintsch, 1986; van Dijk & Kintsch, 1983). Kintsch proposed a cognitive architecture with memory instantiated as an associative network consisting of nodes containing knowledge represented as propositions. Kintsch distinguished between three types of knowledge:

- world knowledge—information about the current context or task;
- general knowledge—declarative facts that are independent of the context; and
- plan element knowledge—the if/then rules representing procedural knowledge

The C-I architecture simulates comprehension in the context of a specific task, such as reading a passage, by use of a set of symbolic production rules that *construct* an associative network of knowledge. The network interconnections are based on superficial similarities between the knowledge nodes independent to the task context. In the second phase, the knowledge network

is *integrated* through a process of spreading activation that results in task-relevant connections being strengthened while irrelevant connections are weakened.

According to Duffy and Knuth (1989):

Hypertext or hypermedia systems have three characteristics: a database of information, referred to as nodes or frames; machine supported links between these nodes that allow for rapid movement through the information; and a consistent user interface for interacting with the hypertext. Furthermore, the linking is not arbitrary, but rather is based on the *semantic relationships between nodes*. (p. 200; emphasis the author)

It not surprising, therefore, that C-I is one of the more useful models addressing hypertext navigation. A recent addition to the C-I architecture, Latent Semantic Analysis, automates the measurement of those semantic relationships.

Latent Semantic Analysis (LSA) computes semantic relatedness based on large corpuses of written text that have been scanned into a database. The word frequencies of each document is compiled into a matrix with the columns representing each word and the rows each document (Kintsch, 2001). The degree of semantic relationship between two words (that is, how frequently they co-occur in a meaningful passage) is represented as a cosine that varies between -1 and $+1$. The cosines are interpreted much like a correlation coefficient: $+1$ would indicate the words always occur together, while 0 represents no relationship. The amount of knowledge LSA has of any given word is represented by vector length—the more experience LSA has with a word, the longer the vector (Landauer, Foltz, & Laham, 1998).

The architecture underlying construction-integration theory of text comprehension has been used to predict comprehension levels of text based on such things as level of domain expertise and text coherence (van Dijk & Kintsch, 1983). While developed originally to model human cognition during the reading of traditional written text, the model has been expanded to include such things as goal planning (Mannes & Kintsch, 1991) and the navigation of hypertext (Blackmon, Polson, Kitajima, & Lewis, 2002; Polson & Lewis, 1990). While highly successful in its application, it is not the only architecture in use. A more extensive architecture exists in the form of ACT-R.

ACT-R

John Anderson and his fellow researchers have been expanding and perfecting the ACT-R model for over 10 years—from ACT to ACT* to ACT-R (Anderson, 1983, 1988; Anderson et al., 2003; Anderson, Fincham, & Douglass, 1999; Anderson, Matessa, & Lebiere, 1997; Anderson & Schunn, 2000). According to Anderson et al. (2003):

While there are good reasons for at least some of the proposals for specialized cognitive modules, there is something unsatisfactory about the result—an image of the mind as a disconnected set of mental specialties. One can ask “how is it all put back together?” An analogy here can be made to the study of the body. Modern biology and medicine have seen a successful movement towards specialization responding to the fact that various body systems and parts are specialized for their functions. However, because the whole body is readily visible, the people who study the shoulder have a basic understanding how their specialty relates to the specialty of those who study the hand and the people who study the lung have a basic understanding of how their specialty relates to the specialty of those who study the heart. Can one say the same of the person who studies categorization and the person who studies on-line inference in sentence processing or of the person who studies decision making and the person who studies motor control?” (pp. 3-4)

ACT-R is a cognitive architecture that attempts to incorporate many of the major research findings and theories from the diverse areas of cognitive psychology and melds them into a coherent whole—and does it with no small success. Before we examine the research, however, let us first examine the architecture.

ACT-R is basically a patchwork of the work of many—it “represents a synthesis of the literature on cognitive psychology and human performance” (Byrne, 2003\$, p. 107). For example:

- ACT-R recognizes the existence of two types of knowledge: declarative and procedural.
- The functioning of the ACT-R visual attention module is based on the work of Posner (Fitts & Posner, 1973), Triesman (Triesman & Gelade, 1980), and Wolfe (1994).

- The functioning of the perceptual-motor module is based on Executive Process Interactive Control (EPIC), a model developed by Kieras and Meyer (1997). Kieras and Meyer, in turn, based EPIC on the constraints discovered by others—such as using Fitts' Law to estimate execution time for aimed movements.

At the heart of ACT-R is a production system with a production cycle set for a duration of 50 msec. ACT-R operates with several restrictions in addition to the timing of the production cycle.

First, ACT-R can only fire one production rule per cycle. When multiple production rules match on a cycle, an arbitration procedure called conflict resolution comes into play. Second, ACT-R has a well-developed theory of declarative memory. Unlike EPIC and Soar, declarative memory elements in ACT-R are not simply symbols. Each declarative element in ACT-R also has associated with it an activation value, which determines whether and how rapidly it may be accessed. Third, ACT-R contains learning mechanisms, but not a pervasive learning system in the same sense as Soar. (Byrne, 2003, p. 110)

In ACT-R, multiple productions may be associated with any given goal. Conflicts between productions are resolved based on a statistically complicated analysis of the probability of accomplishing the goal for each of the competing production systems. The analysis includes such things as the cost (for example, energy and time expended) and expected gains for each production. The values of these costs and gains are learned over time, so ACT-R models can adapt to changes in the environment (Byrne, 2003).

The declarative memory in ACT-R holds such information about what is being attended to in the environment, any goal-related information, and any information needed from long-term memory to accomplish the current task (Pirolli & Card, 1999). ACT-R uses a network model of declarative knowledge. Declarative knowledge is represented as interconnected nodes. When one node is activated, all related nodes are activated as well. This process is similar to the spreading activation found in Kintsch's C-I architecture.

The rest of this article will outline problems with the use of hypertext in educations and how these two cognitive architectures, C-I and ACT-R, can be used to mediate these problems.

HYPertext IN EDUCATION

The rapid adoption of hypertext formats in education is not without controversy. On the one hand, hypertext was greeted by many in the field of education with great enthusiasm and a great deal of hype (Dillon, 1996). On the other hand, hypertext has been much maligned as destroying logical thought. Duffy and Knuth (1989) summarized the prevailing positive pedagogical arguments for the use of hypermedia:

Perhaps the most basic argument is that it opens up the knowledge domain and permits the learner to explore and search out issues of interest to him. This has a motivational impact since it is *learner directed*. More importantly, however, will be the transfer of features of the knowledge domain being explored. Both specific and general transfer have been hypothesized. The specific transfer is of the semantic network of the knowledge domain. That is, it has been suggested that we can use hypermedia to represent the knowledge structure of the expert. Then, as the student explores the knowledge domain he will learn the experts [sic] structure... It has also been argued that exploring the database leads to more *general transfer of a nonlinear way of thinking*. (p. 203)

Referring to the zealous promotion of hypermedia as an educational wonder, Dillon (1996) noted that, "the last decade of empirical evidences suggests that this article of faith, like most religious beliefs, does not defy argument" (p. 26).

Not all in the educational field are strong supporters of the use of hypermedia however. Some view hypermedia as undercutting the linear, logical thought processes developed through traditional education based on the reading of the printed text, and leaves in its place "a haphazard, hypertext-structured thought process (Hokanson & Hooper, 2000). Ultimately, we must turn to empirical evidence as a means of grounding our hopes and theories with facts "to bring about changes in contemporary design contexts and to introduce greater rationality into the discussions of such technologies" (Dillon, 1996, p. 27).

When discussing hypermedia, it is important to distinguish between two kinds of applications: *hyperbases* and *hyperdocuments*. Hyperbases are browseable databases that can be freely explored, whereas, hyperdocuments

are highly structured, with a more constrained access (Wright, 1991b). It is the free-flowing exploration of the hyperbase that is seen as best suited to support the constructivist view-point of discovery learning, while the hyperdocument is seen as “better suited for tasks requiring deeper understanding and learning” (Moreno-Muñoz, Plaza-Alonso, de-Castro-Lozano, & Dormido-Bencomo, 2002, p. 251). The focus of this review is mainly on the hyperbase.

While unstructured hyperbases may suit the constructivist theory, they are not without their problems. There is considerable empirical evidence that navigation and comprehension of material in an unstructured hyperbase format can be difficult—especially for learners new to the material or new to the hypertext medium (Nielsen, 1990). According to Wright (1991a):

This problem tends not to arise with other computer applications. When working with a database, users do not move but rather they command and the information comes to them. Large spread sheets retain cues telling users where they currently are as they move about in the two dimensional array. Word processing documents can be lengthy but they are linear, so page numbers are good location cues. However, in hypertext it is possible to create an irregular patchwork of information that has no structure to be grasped, and therefore no labels that can unambiguously identify where HERE is. In such freedom the reader’s cognitive resources used for planning where to go, and keeping track of where they have been, may become overloaded. (p. 1)

Conklin (1987) defined cognitive overload as “the additional effort and concentration necessary to maintain several tasks simultaneously or trails at one time” (p. 40). Cognitive overload can lead to disorientation. According to Conklin, disorientation is “the tendency to lose the sense of location and direction in a non-linear document system” (p. 40). In other words, the student gets “lost in hyperspace.”

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