37

Adaptive Instructional Systems

Jung Lee
The Richard Stockton College of New Jersey, Pomona, New Jersey

Ok-Choon Park
Institute of Education Sciences, Washington, D.C.

CONTENTS

ABSTRACT

Adaptive instruction embodies all instructional forms that accommodate the needs and abilities of different learners. This chapter summarizes five approaches to adaptive instruction: (1) macro-adaptive instruction; (2) aptitude–treatment interactions (ATI-based); (3) micro-adaptive instruction, including intelligent tutoring systems (ITSs); (4) the adaptive/adaptable hypermedia/Web-based system (AHS); and (5) specific pedagogy-centered systems. These approaches are presented in historical order, beginning with macro-adaptive systems. For each approach, its characteristics and representative systems are discussed. Although each has its own distinctive properties, some similarities can be found among the approaches. Due to the development of information and communication technology (ICT), the structural functions of recent adaptive systems are significantly more powerful than earlier ones. New Web-based systems have functions that simultaneously provide customized learning experiences to masses of individual learners. The challenges now facing researchers and developers are to optimally integrate many different theories, principles, and strategies of learning and instruction with system functions and to prove empirically the effects and value of these systems in real-world environments.

KEYWORDS

Adaptive hypermedia systems (AHSs): Combining micro-adaptive systems and hypermedia systems to provide adaptive/adaptable, hybrid features by presenting learners with choices, along with guidance.

Adaptive instructional systems: Any forms of educational intervention aimed at accommodating individual learner differences.

Aptitude–treatment interactions (ATIs): Adapting specific instructional procedures and strategies to specific learner characteristics (or aptitudes).

Macro-adaptive systems: Allowing different alternatives for choosing instructional goals, curriculum content, and delivery systems, by grouping students.

Micro-adaptive systems: Diagnosing the learner's specific learning needs during instruction and providing instructional prescriptions for the needs.

DEFINITION

A central and persistent issue in educational technology is the planning and provision of instructional environments and conditions that fit and support individually different educational goals and learning abilities (Park, 1996). In general, instructional approaches and techniques that are geared to meet the needs of individually different students in developing knowledge and skills required to learn a task are called *adaptive instruction* (Corno and Snow, 1986). Accordingly, any form of instruction is adaptive, whether it is delivered by teachers or in a technology-based format, if it accommodates different student learning needs and abilities.

Adaptive instruction has a long history and has been implemented in various forms and settings, from group-based, classroom instruction to Web-based, open space instruction. The development of computer technology has provided a powerful tool for developing and implementing sophisticated instructional systems from diagnostic assessment tools to tutoring systems generating individually tailored instructional prescription. Recent advances in information and communication technology (ICT) allow for the delivery of individually customized information and instruction to mass audiences simultaneously. This mass individualization has been increasingly popular and important in education and training communities (De Bra et al., 2004; Karagiannidis et al., 2001; van Merriënboer, 2005).

HISTORY OF ADAPTIVE INSTRUCTIONAL SYSTEMS

The long history of efforts in adapting instruction to an individual student's needs and abilities has been documented by many researchers (Corno and Snow, 1986; Federico et al., 1980; Glaser, 1977; Reiser, 1987; Tobias, 1989; Wang and Lindvall, 1984). Since at least the fourth century B.C., adapting has been viewed as a primary requirement for successful instruction (Corno and Snow, 1986), and adaptive tutoring was the common instructional method until the mid-1800s (Reiser, 1987). Even after graded systems were adopted, the importance of adapting instruction to individual needs was continuously emphasized. Dewey, for example, in his 1902 essay, *Child and Curriculum*, deplored the then current emphasis on a single kind of curriculum development that produced a uniform, inflexible sequence of instruction (Dewey, 1902/1964). Thorndike (1911) argued for a specialization of instruction that acknowledged differences among pupils within a single class as well as specialization of the curriculum for different classes. Since then, various approaches and methods have been proposed to provide adaptive instruction to individually different students (for early systems, see Reiser, 1987).

Since Cronbach (1957) declared that a united discipline of psychology would be interested in not only organisms but also interactions between organisms and treatment variables, numerous studies have been conducted to investigate what kinds of student characteristics should be considered in adapting instruction and how instructional methods and procedures should be adapted to those characteristics (Cronbach, 1967; Cronbach and Snow, 1977; Federico et al., 1980; Snow and Swanson, 1992). Whereas early instructional systems considered only one or two variables, newer adaptive systems using computer technology implement models that have multiple layers, each with many variables. Each adaptive system lies along this complexity continuum, but they can be clustered into several types according to their approaches.

DIFFERENT APPROACHES TO ADAPTIVE INSTRUCTIONAL SYSTEMS

Efforts to develop and implement adaptive instruction have taken five different approaches. Depending on available resources and constraints in the given situation, adaptive instruction can be designed using one or more of these approaches. The first approach is to adapt instruction on a macro-level by allowing alternatives in instructional goals, depth of curriculum content, delivery systems, etc. Most adaptive instructional systems developed as alternatives to the traditional lock-step group instruction in school environments have taken this approach. The second approach is to adapt specific instructional procedures and strategies to specific student characteristics. Because this approach requires the identification of the most relevant learner characteristics (or aptitudes) for instruction and the selection of instructional strategies that best facilitate the learning process of the students with those characteristics, it is based on aptitude–treatment interaction (ATI). The third approach is to adapt instruction on a micro-level by diagnosing the student's specific learning needs during instruction and providing instructional prescriptions for the needs. Intelligent tutoring systems (ITSs) are an example of this approach. The fourth approach is adaptive hypermedia and Web-based systems (AHSs). Although this approach can be considered as an extension of ITS, it has several new features. First, most AHSs apply adaptive/adaptable (hybrid) features by allowing users to initiate their choices, along with guidance (Cristea and Garzotto, 2004). Second, whereas previous adaptive systems are closed corpus systems confined to the program, most AHS applications are Web-based, open corpus systems which allows the possibility of utilizing other Web resources. The fifth is a group of systems that were developed based on specific pedagogical approaches. The pedagogical approaches applied in these systems include constructivism, motivation theory, social learning theory, and metacognition.

Although they are presented as five different approaches, some overlaps exist between categories. Further, an adaptive instructional system may contain characteristics of more than one approach. Also, although this review is intended to be comprehensive, it is certainly not complete. Several relevant endeavors in the field—for example, applications of cognitive load theory to adaptive instruction—are not included in this review because these systems are in the early stages of development.

MACRO-ADAPTIVE INSTRUCTION

Initial attempts at homogeneous grouping had minimal effect because the groups seldom received different kinds of instructional treatments (Tennyson, 1975). In the early 1900s, a number of adaptive systems were developed to better accommodate different student abilities, such as the Burke plan, Dalton plan, and Winnetka plan (Reiser, 1987). The notion of mastery learning was also fostered in the Dalton and Winnetka plans.

Several macro-adaptive instructional systems were developed in the 1960s, 1970s, and 1980s (for a review, see Park and Lee, 2003). Examples of macro-adaptive instructional systems include Keller's Personalized System of Instruction (PSI) (Keller and Sherman, 1974), the Program for Learning in Accordance with Needs (PLAN) (Flanagan et al., 1975), Mastery Learning Systems developed by Bloom and his associates (Block, 1980), Individually Guided Education (IGE) (Klausmeier, 1975), and Individually Prescribed Instructional System (IPI) (Glaser, 1977). Although many macro-level systems have been criticized as being unsystematic, they were practiced in many school classrooms for a long time, and some systems are still used. The Adaptive Learning Environments Model (ALEM) developed by Wang and her associates (Wang, 1980; Wang and Lindvall, 1984; Wang et al., 1995; see also http://www.nwrel.org/scpd/catalog/ModelDetails.asp?ModelID=8) is still implemented in many schools. Another sample of macro-level approaches is the PLATO Learning Management (PLM) system; PLM was a computer-managed instructional (CMI) system with functions to diagnose student learning needs and prescribe instructional activities appropriate for those needs. The PLM could evaluate each student's performance on a test and provide specific instructional prescriptions (Hart, 1981).

As Glaser (1977) pointed out, the development and implementation of an adaptive instructional program in an existing system were complex and difficult. This problem may be the primary reason why most macro-adaptive instructional systems have not been used as successfully and widely as hoped. Computer technology, however, provides a powerful means to overcome at least some of the problems encountered in the development and implementation of adaptive instructional systems.

APTITUDE–TREATMENT INTERACTIONS

Cronbach (1957) suggested that facilitating educational development for a wide range of students requires a wide range of environments suited to their optimal learning. He proposed prescribing one type of instructional sequence for a student with certain characteristics and another type for a student with different characteristics. This strategy has been based on aptitude–treatment interactions (ATIs). Cronbach and Snow (1977) defined *aptitude* as any individual characteristic that increases or impairs the student's probability of success in a given treatment, and they defined *treatment* as variations in the pace or style of instruction.

An Eight-Step Model for Designing ATI-Based Courseware

Carrier and Jonassen (1988) proposed an eight-step model to provide practical guidance for applying the ATI-based model to the design of computer-based instructional (CBI) courseware. This model is basically a modified systems approach to instructional development (Dick and Carey, 1985; Gagné and Briggs, 1979): (1) Identify objectives for the courseware, (2) specify task characteristics, (3) identify an initial pool of learner characteristics, (4) select the most relevant learner characteristics, (5) analyze learners in the target population, (6) select final differences (in the learner characteristics), (7) determine how to adapt instruction, and (8) design alternative treatments. Carrier and Jonassen (1988) also listed important individual variables that influence learning, such as prior knowledge, cognitive styles, and personality variables. For instructional adaptation, they recommended several types of methods: (1) remedial, (2) capitalization/ preferential, (3) compensatory, and (4) challenge. This model seemingly has practical value; however, without theoretically coherent and empirically traceable links among different learner variables and without clearly defined types and levels of learning requirements and instructional strategies for different tasks, the mere application of this model is not likely to produce better results than those of nonadaptive instructional systems.

Limitations of ATI

Since Cronbach (1957) made his proposal, relatively few studies have found consistent results to support the paradigm. As shown in several reviews of ATI research (Berliner and Cahen, 1973; Corno and Snow, 1986; Cronbach and Snow, 1977; Tobias, 1976), intellectual abilities and other aptitude variables were used in many different studies to investigate their interactions with a variety of instructional treatments; however, no convincing evidence was found to suggest that such individual differences were useful variables for differentiating instructional treatments in a homogeneous age group (Glaser and Resnick, 1972; Tobias, 1987).

The inconsistent findings of ATI studies prompted researchers to reexamine the paradigm and propose alternative approaches. According to Tobias (1976, 1987, 1989), a number of limitations and problems in the ATI-based model have been proposed; for example:

- The abilities assumed to be most effective for a particular treatment may not be exclusive (Cronbach and Snow, 1977).
- Abilities required by a treatment may shift as the task progresses (Burns, 1980; Federico, 1983).
- ATIs validated for a particular task and subject area may not be generalizable to other areas (Peterson, 1977; Peterson and Janicki, 1979; Peterson et al., 1981).
- ATIs validated in laboratory experiments may not be applicable to actual classroom situations (Tobias, 1976, 1987, 1989).

Another criticism is that ATI research has tended to be overly concerned with exploration of simple input/output relations between measured traits and learning outcomes (DiVesta, 1975). Because individual difference variables are difficult to measure, the validity and reliability of the measures can be a problem in adapting instruction to the individual differences; however, research in ATI has continued.

Recently, several studies have been conducted to control learning environments using computers; for example, Maki and Maki (2002) examined the interactions of student comprehension skills with course format (online vs. lecture format). After examining the interactions among particular learning types, exploratory behavior, and two different learning environments (rule application vs. rule induction), Shute and Towle (2003) introduced an adaptive e-learning model utilizing ATI.

MICRO-ADAPTIVE INSTRUCTION

Researchers have attempted to establish micro-adaptive instructional models using on-task measures rather than pre-task measures. On-task measures of student behavior and performance, such as response errors, response latencies, and emotional states, can be valuable sources for making adaptive instructional decisions during the instructional process. Such measures taken during the course of instruction can be applied to the manipulation and optimization of instructional treatments and sequences on a much more refined scale (Federico, 1983). Thus, micro-adaptive instructional models using on-task measures are likely to be more sensitive to the student's needs.

A typical example of micro-adaptive instruction is one-on-one tutoring. The tutor selects the most appropriate information and tutoring method for the student based on his or her judgment of the student's learning needs and abilities (Bloom, 1984; Kulik, 1982). As the one-on-one tutorial process suggests, two essential elements of micro-adaptive instruction are the ongoing diagnosis of the student's learning needs and the prescription of instructional treatments based on the diagnosis (Hansen et al., 1977; Holland, 1977; Landa, 1976; Rothen and Tennyson, 1978). Instructional researchers or developers have different views about the variables, indices, procedures, and actions that should be used in the diagnostic and the prescriptive processes (Atkinson, 1976; Rothen and Tennyson, 1977).

Micro-Adaptive Instructional Models

Unlike macro-adaptive models, micro-adaptive models are dynamic and use the temporal nature of learner abilities and characteristics (e.g., current knowledge, motivation level) as a major source of diagnostic information on which instructional treatments are prescribed. By including more variables related to instruction, a typical micro-adaptive model provides a better control process than a macro-adaptive model or programmed instruction in responding to the student's learning needs (Merrill and Boutwell, 1973). As described by Suppes et al. (1976), micro-adaptive models typically use a quantitative representation and trajectory methodology. An important feature of a micro-adaptive model is the timeliness and accuracy for determining and adjusting learning prescriptions during instruction.

Most micro-adaptive models are primarily developed to adapt two instructional variables: the amount of content to be presented and the presentation sequence of the content. Representative examples of micro-adaptive instructional models are mathematical models, multiple regression models, Bayesian probability models, and structural/algorithmic models (for a comprehensive review, see Park and Lee, 2003). The Bayesian probabilistic model and the multiple regression model are designed to select the amount of instruction required to learn a given task using both pre-task and on-task information (Hansen et al., 1977; Park and Tennyson, 1980, 1986; Ross and Anand, 1986; Ross and Morrison, 1986; Rothen and Tennyson, 1977). The structural/algorithmic approach emphasizes that the sequence of instruction should be decided by the content structure of the learning task as well as the student's performance history (Scandura, 1977a,b, 1983).

Regarding treatment variables, some studies (Hansen et al., 1977; Ross and Morrison, 1988) indicated that only prior achievement among pre-task measures (e.g., anxiety, locus of control) provides consistent and reliable information for prescribing the amount of instruction; however, subjects who received the amount of instruction selected based on both pre-task measures and on-task measures needed less time and showed higher test scores than subjects who received the amount of instruction based on only pre-task measures (Park and Tennyson, 1980). The results of the response-sensitive strategies studied by Park and Tennyson (1980, 1986) suggest that the predictive power of pre-task measures, including prior knowledge, decreases while that of on-task measures increases as the instruction progresses.

As reviewed above, a common characteristic of micro-adaptive instructional models is response sensitivity in diagnosing student learning needs and providing instructional prescriptions. Response-sensitive instruction has been used for a long time, from Crowder's simple branching program (1959) and Atkinson's mathematical model of adaptive instruction (1968) to intelligent tutoring systems. Until the late 1960s, technology was not readily available to implement the response-sensitive diagnostic and prescriptive procedures as a general practice outside the experimental laboratory (Hall, 1977).

Intelligent Tutoring Systems

Intelligent tutoring systems (ITSs) were developed with the application of artificial intelligence (AI) techniques. Because the goal of ITSs is to provide adaptive instruction by intelligently diagnosing students' learning needs and progress in a response-sensitive manner, they are considered micro-level adaptive instructional systems. ITSs have three main components: a representation of the content to be taught (expert or domain model), an inherent teaching or instructional strategy (tutor or teaching model), and mechanisms for understanding what the student does and does not know (student model) (Akhras and Self, 2002; Shute and Psotka, 1996; Wenger, 1987). AI methods for the representation of knowledge (e.g., production rules, semantic networks, scripts frames) and problems make it possible for the ITS to generate and present knowledge to students based on their performance on the task rather than selecting the knowledge according to the predetermined branching rules. The capacity to make inferences about the cause of a student's misconceptions and his or her learning needs allows the ITS to make decisions based on qualitative data, unlike most micro-adaptive models based on solely quantitative data.

Furthermore, ITS techniques provide a powerful tool for effectively capturing human learning and teaching processes. It has apparently contributed to a better understanding of cognitive processes involved in learning specific skills and knowledge (Shute and Psotka, 1996). Some ITSs provided research environments for investigating specific instructional strategies and tools for modeling human tutors and simulating human learning and cognition (Koedinger and Anderson, 1998; Seidel and Park, 1994; Shute and Psotka, 1996). Recently, ITSs were expanded to enhance metacognition (Aleven et al., 2001; White et al., 1999); however, it has been noted that ITS developers have failed to incorporate many valuable learning principles and instructional strategies developed by instructional researchers and educators (Park et al., 1987). Ohlsson (1987, 1993) and others criticized ITS and other computer-based interactive learning systems for their limited range and adaptability of teaching actions compared to rich tactics and strategies employed by human expert teachers. Cooperative efforts among experts in different domains, including learning/instruction and artificial intelligence, are required to develop more powerful adaptive systems using the ITS methods and techniques (Park and Seidel, 1989; Seidel et al., 1989).

Applying ATI to Micro-Level Adaptive Systems

To integrate the ATI-based approach in a micro-adaptive model, Tennyson and Christensen (1988; also see Tennyson and Park, 1987) proposed a two-level model of adaptive instruction based on the findings of their own research. First, this computer-based model allows the computer tutor to establish conditions of instruction based on learner aptitude variables (cognitive, affective, and memory structure) and context structure. Second, the computer tutor provides moment-to-moment adjustments of instructional conditions by adapting the amount of information, example formats, display time, sequence of instruction, instructional advisement, and embedded refreshment and remediation. The micro-level adaptation is based on the student's *on-task performance*, and the procedure is *response sensitive* (Park and Tennyson, 1980). The amount of information to be presented and the time to display the information on the computer screen are determined through the continuous decision-making process based on on-task performance data. The selection and presentation of other instructional strategies (sequence of examples, advisement, and embedded refreshment and remediation) are determined based on the evaluation of the on-task performance.

Evidence shows that some aptitude variables (e.g., prior knowledge, interest, intellectual ability) are important predictors in selecting instructional treatments (Tobias, 1994; Whitener, 1989); however, some studies (Park and Tennyson, 1980, 1986) suggest that the predictive value of aptitude variables decreases as the learning process continues. In contrast, the diagnostic power of on-task performance increases because it reflects the most updated and integrated reflection of aptitude and other variables involved in the learning. The decrease in the predictive power of the premeasured aptitude variables and the increase in that of on-task performance can be represented as shown in Figure 37.1.

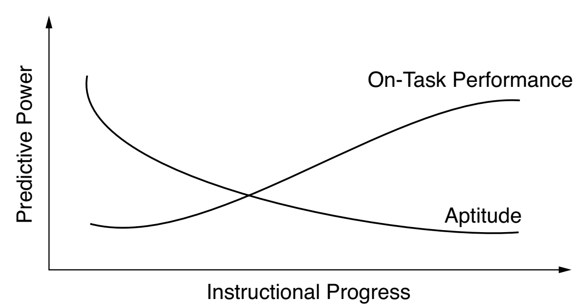

Figure 37.1 Predictive power of aptitudes and on-task performance.

In the two-stage approach, the student is assigned initially to the best instructional alternative based on the aptitude measured prior to instruction, and then response-sensitive procedures are applied as the student's response patterns emerge to reflect his or her knowledge or skills on the given task. A representative example of this two-stage approach is the Bayesian adaptive instructional model. As the process for estimating student learning needs continues using a Bayesian probability model, the value of the pretest performance data becomes less important and recent performance data become more important. The effectness of the two-stage approach has been empirically supported (Park and Tennyson, 1980, 1986).

ADAPTIVE HYPERMEDIA SYSTEMS

In the early 1990s, when researchers incorporated the concepts of hypermedia/hypertext with intelligent tutoring systems, adaptive hypermedia systems (AHSs) were born (Beaumont, 1994; Brusilovsky et al., 1996; De Bra et al., 2005; Fischer et al., 1990; Gonschorek and Herzog, 1995; Hohl et al., 1996; Kay and Kummerfeld, 1994). An AHS utilizes hyperlinks, and its technical approach, including a user-model-based interface, is similar to an ITS; however, AHSs differ from both micro-adaptive systems (including ITSs) and conventional hypermedia systems in terms of adaptability/adaptivity.

In general, computer-based instructional systems that allow the user to choose certain parameters and adapt the behavior of these systems are referred to as *learner-controlled instruction* (Williams, 1996) or *adaptable systems* (Cristea and Garzotto, 2004; Fink et al., 1998; Opperman, 1994), whereas adaptive systems in which behaviors are automatically based on the user's needs are referred to as *program-controlled* (*system-controlled*) *instruction*, or *adaptive systems*.*

Conventional hypermedia learning environments are nonadaptive, as they provide the same content and the same set of links to all learners; however, they are adaptable because links or tasks to be presented next are determined by the learner's actions. Adaptability without adaptivity may lead the learner along a poor path (Steinberg, 1991; Williams, 1996). Unlike conventional hypermedia environments, an AHS is adaptive, providing content and links based on the individual user's needs and characteristics; for example, the *next* button in an AHS may not be different in appearance but it will take different users to different pages (Schwarz et al., 1996).

Traditional micro-adaptive instructional systems are adaptive but not adaptable. They control the instructional process and activities based on an evaluation of student learning needs and abilities, but they do not allow students to control the process of adaptation. In contrast, most AHSs allow users to initiate their own choices; for example, an AHS might provide *a suggested set of most relevant links* based on the system's assessment of the user's needs and characteristics (Brusilovsky, 1994).

Because an AHS includes both learner and program control, it is also referred to as an *adaptive/adaptable* hybrid system (Cristea and Garzotto, 2004). Oppermann developed and tested the adaptive/adaptable system Flexcel. He concluded that adaptivity and adaptability should receive benefits from each other (Oppermann, 1994).

Another difference between AHSs and micro-adaptive systems is that, except for a few early AHSs developed before the advent of the Web, AHSs are Web based. As Brusilovsky (2003) pointed out, when using the Web platform course instructors or developers can use not only the *closed corpus* course material in the system but also *open corpus* Web sources. Open corpus Web sources were not available for previous adaptive systems.

Since the mid-1990s, with the advent of the Web, AHSs have grown rapidly (Brusilovsky, 2001). Now, the Web is the choice of all AHSs, and AHSs are now referred to as *adaptive Web-based hypermedia* or *Web-based adaptive hypermedia*. Due to its large variety of users, the Web is an ideal candidate for adaptivity and has served as a platform for AHS research and development (Brusilovsky, 2000). Many AHSs have been developed for education and training purposes, such as hypermedia, e-learning, virtual museums, and online information systems (Brusilovsky, 2003; Cristea, 2005). AHS research and development have been extended to the development of AHS authoring tools, such as Multibook (Steinacker et al., 1998), InterBook (Brusilovsky et al., 1998), ACE (Specht and Oppermann, 1998), KBS Hyperbook (Henze and Nejdl, 1999, 2001), AHA! (De Bra et al., 2003), ADAPTS (Brusilovsky and Cooper, 2002), WHURLE (Moore et al., 2004), and SmexWeb (Albrecht et al., 2000). Also, the functions of AHSs have been improved, from the application of simple one-layered, knowledge-based user models to sophisticated multiple-layered user models (Brown et al., 2005).

* These definitions of the words *adaptive* and *adaptable* are not employed universally; for example, Leutner (2004) referred to learning environments that are macro-adaptive as *adaptable* and those that are micro-adaptive as *adaptive*.

AHS Taxonomies

In 1997, the Adaptive Hypertext and Hypermedia Discussion forum (Eklund and Sinclair, 2000) defined adaptive hypermedia systems as "all hypertext and hypermedia systems which reflect some features of the user in the user model and apply this model to adapt various visible and functional aspects of the system to the user." More specifically, an adaptive hypermedia system should: (1) be based on hypermedia or hypertext, (2) have a user model, (3) have a domain model, and (4) be modifiable (adaptive) based on information contained in the user-model (Eklund and Sinclair, 2000).

Brusilovsky (1996) developed the first taxonomy of AHSs which distinguishes two areas of adaptation: (1) adaptation of the content of the page, called *content-level adaptation* or *adaptive presentation*, and (2) behavior of the links, called *link-level adaptation* or *adaptive navigation support*. The goal of adaptive presentation is to adapt the content of a hypermedia page to the learner's goals, knowledge, and other information stored in the user model. The techniques of adaptive presentation are to adapt the content of a page accessed by a particular user to the user's current knowledge, goals, and other characteristics or to provide not only text but also a set of various multimedia items. The goal of adaptive navigation support is to assist learners in finding their optimal paths in hyperspace by adapting link presentation and functionality to the goals, knowledge, and other characteristics of individual learners. Direct guidance; sorting; annotation; link hiding, disabling, and removal; and link generation are ways to provide adaptive links to individual learners (Brusilovsky, 2000, 2003, 2004; Brusilovsky and Pesin, 1994, 1998; Brusilovsky and Rizzo, 2002; Brusilovsky and Vassileva, 1996; De Bra, 2000; Kayama and Okamoto, 1998).

Brusilovky's taxonomy was refined by others. Cristea and Calvi (2003) presented three layers of adaptation from direct adaptation techniques (low level), adaptation language (medium level), and adaptation strategies (high level). The low level is based on Brusilovky's taxonomy, the medium level refers primarily to goal- or domain-oriented adaptation techniques, and the high level refers to adaptation techniques for detecting learner's information-processing strategies and cognitive styles (Brown et al., 2005; Calvi and Cristea, 2002; Cristea and Calvi, 2003; Cristea and De Bra, 2002). My Online Teacher (MOT) is a representative sample of AHS authoring tools that have integrated the three layers of adaptation techniques (Brown et al., 2005; Cristea and Calvi, 2003).

Limitations and Challenges

As reviewed earlier, two features distinguish AHSs from micro-adaptive systems: (1) adaptivity/adaptability and (2) open corpus learning environments. However, these features impose new challenges. Williams' comprehensive review (1996) of learner-controlled vs. program-controlled instruction revealed that learner-controlled (adaptable) systems and program-controlled (adaptive) systems have different strengths and weaknesses. According to Williams, each type of system is more effective than the other for some people and under certain conditions (for those conditions, see Williams, 1996). This finding suggests that a system with the combined functions of adaptability and adaptivity would be more effective than a system with only adaptable or adaptive functions. AHSs were developed to provide hybrid systems; however, decisions about how to design adaptive/adaptable systems are still made on an *ad hoc* basis without an adequate theoretical or empirical rationale for the design of these hybrid systems (Avgeriou et al., 2004; Cristea and De Bra, 2002). Adaptivity has risen to a new level; the question now is how to balance adaptivity and adaptability in a system.

A conceptual model for adaptable/adaptive systems can be found in Park's (1996) proposal of *on-task adaptive learner-control* (see Figure 37.1), in which learners have more freedom in choosing learning activities as the instruction progresses. In the beginning stage of learning, the student's familiarity with the subject knowledge and its learning requirements would be relatively low, and the student would not be able to choose the best strategies for learning. As the instruction and learning continue, however, the student's familiarity with the subject and ability to learn it would increase, thus enabling the student to make better decisions in selecting strategies for learning the subject. This argument is supported by research (Carrier, 1984; Ross and Rakow, 1981; Seidel et al., 1978; Snow, 1980). An on-task adaptive learner control system will decide not only when is the best time for giving the learner-control option but also what kind of control options (e.g., selection of contents, learning activities) should be given based on the student's on-task performance.

Cristea and Garzotto (2004) identified a set of *design variables* or *problem classes* to develop a taxonomy of adaptive/adaptable educational hypermedia: learner model, instructional strategy, instructional view, detection mechanism, and adaptation mechanism. Also, they provided typical problems that a developer might face and design guidelines for each of the problems. Although the guidelines are not yet complete, the taxonomy can be used as a starting point for establishing the design standards of adaptive/adaptable systems, including methods and procedures (Cristea and De Bra, 2002). Empirical study should be conducted to validate and refine these standards.

Web-based AHSs may or may not utilize open corpus resources in the Web; however, designing an AHS that utilizes the open corpus hyperspace is a challenging task. Brusilovsky (2003) pointed out that simply providing external links to multiple sources is not considered adaptive support for students. An important question is how the system provides *adaptive open resources* for students. Many systems and techniques have been developed to expose users to information relevant only to them (Hanani et al., 2001). Several Web-authoring tools, such as WHURLE (Moore et al., 2004) and KBS Hyperlink (Henze and Nejdl, 2001), generate hyperlinks not only inside of the lesson but also to external Web resources based on learners' previous activities. The adaptive Web recommendation (AWR) system is also another method for providing adaptive navigation support technologies for open corpus learning environments (Brusilovsky, 2004). Whereas typical AHSs attempt to adapt to various aspects of the users and provide a rich set of adaptive navigation support techniques in closed learning environments, AWRs focus on one aspect—user interest—and provide relevant external links. Web Knowledge Sea was developed utilizing AWR techniques (Brusilovsky, 2004; Brusilovsky and Rizzo, 2002). Providing adaptive navigational support is another important issue not only for the development of adaptive systems but also for the development of information and communication technology. With the steadily growing Semantic Web, which provides a generic structure for producing machine-processable Web content (see http://www.w3.org/2001/sw), adaptive navigational support will become more feasible.

Reusability, a long-standing problem in computer-based adaptive instructional systems, continues to plague those working with AHSs. Until recently, AHSs were domain-specific applications in particular systems only; therefore, it was difficult to reuse the technology in one system for the development of another system. Research is currently in progress to develop adaptation technology for establishing uniform standards (Brusilovsky, 2003; Cristea, 2004; de Assis et al., 2004). The Minerva project is an example. The goal of the project was to establish a European platform of standards, guidelines, techniques, and tools for user-model-based adaptability and adaptation (see http://wwwis.win.tue.nl/~acristea/HTML/Minerva/). This standardization effort is expected to address the reusability issue. Meta-adaptive models and adaptation standard techniques for AHSs have been tested (de Assis et al., 2004).

ADAPTIVE SYSTEMS SUPPORTING SPECIFIC PEDAGOGICAL APPROACHES

Andriessen and Sandberg (1999) noted that adaptive computer-based instruction mainly focuses on the acquisition of conceptual and procedural knowledge, identification of common misconceptions in specific domains, and interactions between the program (or tutor) and students. As mentioned earlier, adaptive instructional systems were criticized for their limited range of teaching actions compared to human expert teachers. Researchers began to incorporate more complex pedagogical approaches, such as constructivist learning, contingent learning strategies, motivational competence, metacognitive strategies, and collaborative learning in adaptive instructional systems. These five adaptive approaches are not mutually exclusive, but they can be distinguished from one another in terms of their primary thrust. Although researchers are applying other pedagogical approaches to adaptive instructional systems, these five were selected to provide an overview of the impact of pedagogical approaches on the field.

Constructivist Adaptive Systems

Constructivist learning theories emphasize active roles for learners to construct their own knowledge through experiences in a learning context in which the target domain is integrated. To implement constructivist principles into computer-based learning environments, researchers developed the concept of intelligent learning environments (ILEs), which emphasize the facilitatory role of the system as opposed to the tutoring role (Akhras, 2004; Brusilovsky, 1994).

Most adaptive instructional systems utilized representation of knowledge, inference of the learner's state of knowledge, and planning of instructional steps (Akhras and Self, 2000). Akhras and Self argued that "alternative views of learning, such as constructivism, may similarly benefit from a system intelligence in which the mechanisms of knowledge representation, reasoning, and decision making originate from a formal interpretation of the values of that view of learning" (p. 345). Constructivist intelligent systems shift the focus from a model of *what* is learned to a model of *how* knowledge is learned (Akhras and Self, 2000).

To model this facilitatory role, researchers (Akhras, 2004; Akhras and Self, 2000, 2002) proposed four important considerations when designing these systems: situation-based contexts, learning interactions in situation, time-extended processes of interaction, and affordances of learning situations. Their approach was implemented in INCENSE (INtelligent Constructivist ENvironment for Software Engineering learning). KBS Hyperbook is another example of constructivist AHS (Henze and Nejdl, 1999).

Contingent Teaching Systems

According to Vygotsky's theory (1978), providing immediate and appropriately challenging activities and contingent teaching based on a learner's behavior is important for that learner to progress to the next level of learning. He believed minimal levels of guidance are the best for learners. Recently, this theory has been applied in several different ways to computer-based instruction. As compared to traditional adaptive instruction, a contingent teaching system has no global model of the learner. A learner's performance is local, and the situation is constrained by contingencies in the learner's current activity. Because the tutor's actions and reactions should be occurring in response to the learner's inputs, the theory promotes an active view of the learner and an account of learning as a collaborative and constructive process (Wood and Wood, 1996). Contingent tutoring systems generally provide two assessment methods: model tracing and knowledge tracing (du Boulay and Luckin, 2001). The purpose of model tracing is to keep track of all of the student's actions as the problem is solved and to flag errors as they occur. It also adapts the help feedback based on specific problem-solving contexts. The purpose of knowledge tracing is to choose the next problem that is *appropriately challenging* so the students can move in a timely but effective manner through the curriculum. Examples of contingent teaching systems include SHERLOCK (Lesgold, 2001; Lesgold et al., 1992), QUADRATIC tutor (Wood and Wood, 1999), DATA (Wood et al., 1998), Ecolab (Luckin and du Boulay, 1999), and M-Ecolab (Rebolledo Mendez et al., 2006).

Motivation-Based Adaptive Systems

Some new adaptive instructional systems take into account student motivation. Proponents suggest that a comprehensive adaptive instructional plan should consist of a traditional instructional plan combined with a motivational plan (del Soldato and du Boulay, 1995; du Boulay and Luckin, 2001; Wasson, 1990). De Vicente and Pain (2002) have developed a model called the *motivation model*, which diagnoses a student's motivational state based on several variables (i.e., control, challenge, independence, fantasy, confidence, sensory interest, cognitive interest, effort, satisfaction). COSMO (Lester et al., 1999) supports a pedagogical agent that can incorporate nonverbal feedback and conversational signals such as its facial expression, its tone of voice, its gestures, and the structure of its utterances to indicate its own affective state and to increase students' motivation during its interactions with learners.

Metacognition-Based Adaptive Systems

Metacognitive skills enable students to assess their own learning processes. As ICT-based individualized instruction, including online learning environments, becomes increasingly prevalent, metacognitive and self-regulatory processes are becoming more important in the design of systems (Azevedo, 2005a,b; Quintana et al., 2005; Zimmerman and Tsikalas, 2005). In contrast, most early tutoring systems did not promote students' metacognitive thinking (Carroll and McKendree, 1987).

White et al. (1999) argued that metacognitive processes can be easily understood and observed in a multiagent social system that integrates cognitive and social aspects of cognition within a social framework. Based on this conceptual framework, they developed the SCI-WISE program, which houses a community of software agents, such as an Inventor, an Analyzer, and a Collaborator. The agents provide strategic advice and guidance to learners as they undertake research projects and as they reflect on and revise their inquiry; therefore, students express their metacognitive ideas as they undertake complex sociocognitive practices. Through this exercise, students develop explicit theories about the social and cognitive processes required for collaborative inquiry and reflective learning (White et al., 1999).

Another example focusing on improving metacognitive skills is the Geometry Explanation Tutor (GET) developed by Aleven et al. (2001). They argued that self-explanation is an effective metacognitive strategy. Having students explain examples or problem-solving steps helps them learn with greater understanding (Aleven et al., 2003a,b; Chi et al., 1989). Aleven and his associates conducted experimental studies to test the effects of GET. The results provided positive effects on learning outcomes.

The ability to pursue help effectively and efficiently when needed is an important metacognitive skill. Aleven and his associates (Aleven et al., 2003c, 2006) also developed Help-Seeking Tutor Agent, which helps students become better help seekers. They embedded it within their adaptive instructional system, Geometry Cognitive Tutor, and tested whether Help-Seeking Tutor Agent helped students to be better help seekers and to learn better as a result (Aleven et al., 2004). The results showed that the more help-seeking errors students made with the system, the less they learned. Other research (Roll et al., 2006) revealed that, although Help-Seeking Tutor Agent achieved positive effects because students followed its advice, students did not internalize the help-seeking principles.

Collaborative Learning Systems

One of new pedagogical approaches incorporated in adaptive instructional systems is collaborative learning (Söller et al., 2005). Effective collaboration with peers is a powerful learning experience; however, simply placing students in a group and assigning a task to the group does not produce a valuable learning experience for them (Söller, 2001). Teachers (tutors in computer-based systems) should provide strategies for students to experience collaborative learning effectively and interestingly. Through the use of an intelligent collaborative system, Söller (2001) identified five characteristics of effective collaborative learning behaviors: (1) participation, (2) social grounding, (3) performance analysis and group processing, (4) application of active learning conversation skills, and (5) promotive interactions. Söller and her colleagues (2005) developed a conceptual framework, the Collaboration Management Cycle, represented by a feedback loop for the five-phased behaviors.

Although collaborative learning systems are still in development (Jermann et al., 2004; Or-Bach and van Joolingen, 2004; Söller et al., 2005), their contributions to adaptive instructional systems will be significant; they not only facilitate student group activities but also help educators and researchers better understand group interactions and determine how to support collaborative learning better. Appropriate combinations of sound pedagogical approaches such as the ones described above with the structural features and functions of adaptive/adaptable systems will further improve the technical capacity and instructional effectiveness of the systems.

CONCLUSION

Adaptive instruction has a long history. Systematic efforts to develop adaptive instructional systems began in the early 1900s. Adaptive instructional systems have embodied different approaches: macro-adaptive, ATI-based, micro-adaptive (including ITS), and adaptive/adaptable hybrid systems, as well as other approaches that incorporate different pedagogical perspectives. Using interactive computer technology, a number of different micro-adaptive instructional systems have been developed; however, early applications were mostly in laboratory environments because of the limitations of their functional capabilities to handle complex learning and instructional processes.

Since the 1990s, with the advent of the Web and AHSs, adaptive instructional applications have moved out of the labs and into classrooms and workplaces. During the last decade, numerous AHS systems have been developed; however, the dearth of empirical evidence and weak theoretical foundations supporting their effectiveness (Shapiro and Niederhauser, 2004) remain as a hindrance for the wider use of the systems in school education and industry training. It is a difficult and challenging task to develop technically robust, theoretically sound, and empirically valid systems. Research and development on new pedagogical approaches in adaptive systems may provide stronger theoretical foundations for the development of future systems. AHS technology in collaboration with the Semantic Web may lead to standardized open adaptation technology for the development of future adaptive systems. If more theoretically sound and technically robust systems are developed, it becomes more likely that the effects of the systems will be supported in empirical evaluations.

REFERENCES

Akhras, F. N. (2004). From Modelling Teaching Strategies to Modelling Affordances. Paper presented at Workshop on Modelling Human Teaching Tactics and Strategies, August 30, Maceio, Alagoas, Brazil (http://www.cenpra.gov.br/noticiaseeventos/its04workshop/akhras.pdf).

Akhras, F. N. and Self, A. J. (2000). System intelligence in constructivist learning. *Int. J. Artif. Intell. Educ.*, 11(4), 344–376.

Akhras, F. N. and Self, J. A. (2002). Beyond intelligent tutoring systems: situations, interactions, processes and affordances. *Instruct. Sci.*, 30(1), 1–30.

Albrecht, F., Koch, N., and Tiller, T. (2000). SmexWeb: An adaptive Web-based hypermedia teaching system. *J. Interact. Learn. Res.*, 11(3/4), 367–388.

Aleven, V., Popescu, O., and Koedinger, K. R. (2001). Towards tutorial dialog to support self-explanation: adding natural language understanding to a cognitive tutor. In *Artificial Intelligence in Education: AI-ED in the Wired and Wireless Future*, edited by J. Moore, L. Redfield, and W. Johnson, pp. 246–255. Amsterdam: IOS Press.

Aleven, V., Koedinger, K. R., and Popescu, O. (2003a). A tutorial dialog system to support self-explanation: evaluation and open questions. In *Proceedings of the 11th International Conference on Artificial Intelligence in Education*, *AI-ED 2003*, edited by U. Hoppe, F. Verdejo, and J. Kay, pp. 39–46. Amsterdam: IOS Press.

Aleven V., Popescu, O., Ogan, A., and Koedinger, K. R. (2003b). A formative classroom evaluation of a tutorial dialogue system that supports self-explanation. In *Supplemental Proceedings of the 11th International Conference on Artificial Intelligence in Education*, *AIED 2003*. Vol. VI. *Workshop on Tutorial Dialogue Systems: With a View toward the Classroom*, edited by V. Aleven, U. Hoppe, J. Kay, R. Mizoguchi, H. Pain, F. Verdejo, and K. Yacef, pp. 345–355. Sydney: School of Information Technologies, University of Sydney.

Aleven, V., Stahl, E., Schworm, S., Fischer, F., and Wallace, R. M. (2003c). Help seeking and help design in interactive learning environments. *Rev. Educ. Res.*, 73(2), 277–320.

Aleven, V., McLaren, B. M., Roll, I., and Koedinger, K. R. (2004). Toward tutoring help seeking: applying cognitive modeling to meta-cognitive skills. In *Proceedings of the Seventh International Conference on Intelligent Tutoring Systems (ITS-2004)*, edited by J. C. Lester, R. M. Vicari, and F. Paraguacu, pp. 227–239. Berlin: Springer-Verlag.

Aleven V., McLaren, B. M., Roll, I., and Koedinger, K. R. (2006). Toward meta-cognitive tutoring: a model of help-seeking with a cognitive tutor. *Int. J. Artif. Intell. Educ.*, 16, 101–130.

Andriessen, J. and Sandberg, J. A. C. (1999) Where is education heading and how about AI? *Int. J. Artificial Intelligence in Education*, 10, 130–150.

Atkinson, C. R. (1968). Computerized instruction and the learning process. *Am. Psychol.*, 23, 225–239.*

Atkinson, C. R. (1976). Adaptive instructional systems: some attempts to optimize the learning process. In *Cognition and Instruction*, edited by D. Klahr, pp. 81–108. New York: Wiley.*

Avgeriou, P., Vogiatzis, D., Tzanavari, A., and Retalis, S. (2004). Design patterns in adaptive Web-based educational systems: an overview. In *Advanced Technology for Learning: Innovations in Advanced Technology for Learning: Authoring for Adaptive Educational Hypermedia*. Calgary, Canada: ACTA Press.

Azevedo, R. (2005a). Computer environments as metacognitive tools for enhancing learning. *Educ. Psychol.*, 40(4), 193–197.

Azevedo, R. (2005b). Using hypermedia as a metacognitive tool for enhancing student learning? The role of self-regulated learning. *Educ. Psychol.*, 40(4), 199–209.

Beaumont, I. (1994). User modeling in the interactive anatomy tutoring system NATOM-TUTOR. *User Model. User-Adapt. Interact.*, 4, 121–145.

Berliner, D. C. and Cahen, L. S. (1973). Trait-treatment interaction and learning. *Rev. Res. Educ.*, 1, 58–94.

Block, J. H. (1980). Promoting excellence through mastery learning. *Theory Pract.*, 19(1), 66–74.

Bloom, B. S. (1984). The 2 sigma problem: The search for methods of group instruction as effective as one-to-one tutoring. *Educ. Res.*, 13, 4–16.*

Brown, E., Cristea, A., Stewart, C., and Brailsford, T. (2005). Patterns in authoring of adaptive educational hypermedia: a taxonomy of learning styles. *Educ. Technol. Soc.*, 8(3), 77–90 (special issue on authoring of adaptive educational hypermedia).

Brusilovsky, P. (1994). Adaptive hypermedia: the state of the art. In *Proceedings of East–West International Conference on Multimedia, Hypermedia and Virtual Reality*, September 14–16, Moscow, edited by P. Brusilovsky, pp. 24–29. Moscow: ICSTI.*

Brusilovsky, P. (1996) Methods and techniques of adaptive hypermedia. *User Model. User-Adapt. Interact.*, 6(2–3), 87–129.*

Brusilovsky, P. (2000). Adaptive hypermedia: from intelligent tutoring systems to Web-based education. In *Intelligent Tutoring Systems*, LNCS 1839, edited by G. Gauthier, C. Frasson, and K. Van Lehn, pp. 1–7. Berlin: Springer.

Brusilovsky, P. (2001). Adaptive hypermedia. *User Model. User-Adapt. Interact.*, 11, 87–110.

Brusilovsky, P. (2003). Adaptive navigation support in educational hypermedia: the role of student knowledge level and the case for meta-adaptation. *Br. J. Educ. Technol.*, 34(4), 487–497.

Brusilovsky, P. (2004). Adaptive navigation support: from adaptive hypermedia to the adaptive Web and beyond. *PsychNology*, 2(1), 7–23.

Brusilovsky, P. and Cooper, D. W. (2002). Domain, task, and user models for an adaptive hypermedia performance support system. In *Proceedings of 2002 International Conference on Intelligent User Interfaces*, January 13–16, San Francisco, CA, edited by Y. Gil and D. B. Leake, pp. 23–30. Washington, D.C.: ACM Press.

Brusilovsky, P. and Pesin, L. (1994). An intelligent learning environment for CDS/ISIS users. In *Proceedings of the Interdisciplinary Workshop on Complex Learning in Computer Environments: Technology in School, University, Work and Life-Long Education (CLCE94)*, May 16–19, Joensuu, Finland, edited by J. J. Levonen and M. T. Tukianinen, pp. 29–33.

Brusilovsky, P. and Pesin, L. (1998). Adaptive navigation support in educational hypermedia: an evaluation of the ISIS-Tutor. *J. Comput. Inform. Technol.*, 6(1), 27–38.

Brusilovsky, P. and Rizzo, R. (2002). Map-based horizontal navigation in educational hypertext. *J. Digit. Inform.*, 3(1) (http://jodi.ecs.soton.ac.uk/Articles/v03/i01/Brusilovsky/).

Brusilovsky, P. and Vassileva, J. (1996). Preface. *User Model. User-Adapt. Interact.*, 6(2–3), v–vi.

Brusilovsky, P., Schwarz, E., and Weber, G. (1996). ELM-ART: an intelligent tutoring system on the World Wide Web. In *Intelligent Tutoring Systems*, LNCS 1086, edited by C. Frasson, G. Gauthier, and A. Lesgold, pp. 261–269. Berlin: Springer.

Brusilovsky, P., Eklund, J., and Schwarz, E. (1998). Web-based education for all: a tool for developing adaptive courseware. *Comput. Netw. ISDN Syst.*, 30(1–7), 291–300.

Burns, B. R. (1980). Relation of aptitude learning at different points in time during instruction. *J. Educ. Psychol.*, 72, 785–797.

Calvi, L. and Cristea, A. I. (2002). Towards generic adaptive systems: analysis of a case study. *Adaptive Hypermedia and Adaptive Web-Based Systems: Proceedings of AH'02*, edited by P. De Bra, pp. 79–89. Berlin: Springer-Verlag (http://wwwis.win.tue.nl/~acristea/Conferences/02/AH02/calvi-cristea-final-w-header-ah2002.pdf).

Carrier, C. (1984). Do learners make good choices? *Instruct. Innov.*, 29, 15–17, 48.

Carrier, C. and Jonassen, D. H. (1988). Adapting courseware to accommodate individual differences. In *Instructional Designs for Microcomputer Courseware*, edited by D. Jonassen, pp. 61–96. Mahwah, NJ: Lawrence Erlbaum Associates.

Carroll, J. and McKendree, J. (1987). Interface design issues for advice-giving expert systems. *Commun. ACM*, 30(1), 14–31.

Chi, M., Bassok, M., Lewis, M., Reimann, P., and Glaser, R. (1989). Self-explanations: how students study and use examples in learning to solve problems. *Cogn. Sci.*, 13, 145–182.

Corno, L. and Snow, R. E. (1986). Adapting teaching to individual differences among learners. In *Handbook of Research on Teaching*, edited by M. Wittrock, pp. 605–629. New York: Macmillan.*

Cristea, A. I. (2004). Is semi-automatic authoring of adaptive educational hypermedia possible? *Adv. Technol. Learn.*, 1(4), 227–236.

Cristea, A. I. (2005). Authoring of adaptive hypermedia; adaptive hypermedia and learning environments. In *Advances in Web-Based Education: Personalized Learning Environment*, edited by S. Y. Chen and G. D. Magoulas. Hershey: IDEA (http://wwwis.win.tue.nl/~acristea/Chen/AHChenBookChapt-camera Ready2. doc).

Cristea, A. I. and Calvi, L. (2003). *The Three Layers of Adaptation Granularity*, LNCS 2702, Berlin: Springer.

Cristea, A. I. and De Bra, P. (2002). ODL Education Environments Based on Adaptability and Adaptivity. Paper presented at E-Learn'2002 World Conference on E-Learning in Corporate, Government, Healthcare, and Higher Education, October 15–19, Montreal, (http://wwwis.win.tue.nl/~acristea/Conferences/02/ELEARN02/Cristea-Adaptation-Adaptability.pdf).

Cristea, A. I. and Garzotto, F. (2004). *Designing Patterns for Adaptive or Adaptable Educational Hypermedia: A Taxonomy*, Morgantown, WV: Association for the Advancement of Computing in Education (http://wwwis.win.tue.nl/~acristea/HTMP/Minerva/papers/Garzotto-Cristea-symposium-patterns-2give.doc).

Cronbach, J. L. (1957). The two disciplines of scientific psychology. *Am. Psychol.*, 12, 671–684.*

Cronbach, J. L. (1967) How can instruction be adapted to individual differences? In *Learning and Individual Differences*, edited by R. M. Gagné, Ed., pp. 353–379, Columbus, OH: Merrill.*

Cronbach, J. L. and Snow, E. R. (1977). *Aptitudes and Instructional Methods: A Handbook for Research on Interactions*. New York: Irvingston.*

Crowder, N. W. (1959). *Automatic Tutoring: The State of Art*. New York: Wiley.

de Assis, P., Schwabe, D., and Barbosa, S. (2004). Meta-models for adaptive hypermedia applications and meta-adaptation. In *Proceedings of ED-MEDIA 2004: World Conference on Educational Multimedia, Hypermedia, and Telecommunications*, edited by P. Kommers and G. Richards, pp. 1720–1727. Morgantown, WV: Association for the Advancement of Computing in Education.

De Bra, P. (2000). Pros and cons of adaptive hypermedia in Web-based education. *J. CyberPsychol. Behav.*, 3(1), 71–77.

De Bra, P., Aroyo, L., and Chepegin, V. (2004). The next big thing: adaptive Web-based systems, *J. Digit. Inform.*, 5(1), Article No. 247 (http://jodi.tamu.edu/Articles/v05/i01/ DeBra/).

De Bra, P., Santic, T., and Brusilovsky, P. (2003). AHA! meets Interbook, and more.... In *Proceedings of World Conference on the E-Learning, E-Learn 2003*, edited by A. Rossett, pp. 57–64. Morgantown, WV: Association for the Advancement of Computing in Education.

De Bra, P., Stash, N., and Smits, D. (2005). Creating Adaptive Web-Based Applications, tutorial at the 10th Int. Conf. on User Modeling, July 25, Edinburgh, Scotland (retrieved from htto://wwwis.win.tue.nl/~debra/um2005/tutorial.pdf).

De Vicente, A. and Pain, H. (2002) Informing the detection of the students' motivational state: an empirical study. In *Intelligent Tutoring Systems: Proceedings of the Sixth International Conference on Intelligent Tutoring Systems*, LCNS 2363, edited by S. A. Cerri, G. Gouarderes, and F. Paraguacu, pp. 933–943. Berlin: Springer.

del Soldato, T. and du Boulay, B. (1995). Implementation of motivational tactics in tutoring systems. *J. Artif. Intell. Educ.*, 6(4), 337–376.

Dewey, J. (1902/1964). The child and the curriculum. In *John Dewey on Education: Selected Writings*, edited by R. D. Archambault, pp. 339–358. New York: Modern Library.

Dick, W. and Carey, L. (1985). *The Systematic Design of Instruction*, 2nd ed. Glenview, IL: Scott, Foresman.

DiVesta, F. J. (1975). Trait-treatment interactions, cognitive processes, and research on communication media. *AV Commun. Rev.*, 23, 185–196.

du Boulay, B. and Luckin, R. (2001). Modeling human teaching tactics and strategies for tutoring systems. *Int. J. Artif. Intell. Educ.*, 12, 235–256.

Eklund, J. and Sinclair, K. (2000) An empirical appraisal of the effectiveness of adaptive interfaces for instructional systems. *Educ. Technol. Soc.*, 3(4), 165–177.

Federico, P. (1983). Changes in the cognitive components of achievement as students proceed through computer-managed instruction. *J. Comput.-Based Instruct.*, 9(4), 156–168.

Federico, P., Montague, E. W., and Snow, E. R. (1980). *Adaptive Instruction: Trends and Issues. Aptitude, Learning and Instruction, Cognitive Process Analyses of Aptitude*. Mahwah, NJ: Lawrence Erlbaum Associates.

Fink, J., Kobsa, A., and Nill, A. (1998). Adaptable and adaptive information provision for all users, including disabled and elderly people. *New Rev. Hypermedia Multimedia*, 4, 163–188.

Fischer, G., Mastaglio, T., Reeves, B., and Rieman, J. (1990). Minimalist explanations in knowledge-based systems. In *Proceedings of 23rd Annual Hawaii International Conference on System Sciences*, edited by L. W. Hoevel and V. Milutinovic, pp. 309–317. Los Alamitos, CA: IEEE.

Flanagan, J. C., Shanner, W. M., Brudner, H. J., and Marker, R. W. (1975). An individualized instructional system: PLAN. In *Systems of Individualized Education*, edited by H. Talmadge Berkeley, CA: McCutchan.

Gagné, R. M. and Briggs, L. J. (1979). *Principles of Instructional Design*, 2nd ed. New York: Holt.

Glaser, R. (1977). *Adaptive Education: Individual, Diversity and Learning*. New York: Holt.*

Glaser, R. and Resnick, L. B. (1972). Instructional psychology. *Annu. Rev. Psychol.*, 23, 207–276.

Gonschorek, M. and Herzog, C. (1995). Using hypertext for an adaptive help system in an intelligent tutoring system. In *Proceedings of AI-ED'95, 7th World Conference on Artificial Intelligence in Education*, edited by J. Greer, pp. 274–281. Morgantown, WV: Association for the Advancement of Computing in Education.

Hall, A. K. (1977). A research model for applying computer technology to the interactive instructional process. *J. Comput.-Based Instruct.*, 3, 68–75.

Hanani, U., Shapira, B., and Shoval, P. (2001). Information filtering: overview of issues, research and systems. *User Model. User-Adapt. Interact.*, 11(3), 203–259.

Hansen, D. N., Ross, M. S., and Rakow, E. (1977). *Adaptive Models for Computer-Based Training Systems*, Annual Report to Navy Personnel Research and Development Center. Memphis, TN: Memphis State University.

Hart, R. S. (1981). Language study and the PLATO IV System. *Studies Lang. Learn.*, 3, 1–24.

Henze, N. and Nejdl, W. (1999). Adaptivity in the KBS Hyperbook System. In *Proc. of the Second Workshop on Adaptive Systems and User Modeling on the World Wide Web (WWW)*, May 11–14, Toronto, Canada (http://www.kbs.uni-hannover.de/~henze/paperadaptivity/Henze.html).

Henze, N. and Nejdl, W. (2001) Adaptation in open corpus hypermedia. *Int. J. Artif. Intell. Educ.*, 12(4), 325–350.

Hohl, H., Boecker, D., and Gunzenhaeuser, R. (1996). Hypadapter: an adaptive hypertext system for exploratory learning and programming. *User Model. User-Adapt. Interact.*, 6(2–3), 131–156.

Holland, G. J. (1977). Variables in adaptive decisions in individualized instruction. *Educ. Psychol.*, 12, 146–161.*

Jermann, P., Soller, A., and Lesgold, A. (2004). Computer software support for CSCL. In *What We Know About CSCL … and Implementing It in Higher Education*, edited by P. Dillenbourg, J. W. Strijbos, P. A. Kirschner, and R. L. Martens pp. 141–166. Boston, MA: Kluwer.

Karagiannidis, C., Sampson, D., and Cardinali, F. (2001). Integrating adaptive educational content into different courses and curricula. *Educ. Technol. Soc.*, 4(3), 37–44

Kay, J. and Kummerfeld, J. R. (1994). An individualized course for the C programming language. In *Proceedings of the Second International WWW Conf.*, October 17–20, Chicago, IL (http://www.cs.usyd.edu.au/~bob/kay-kummerfeld.html).

Kayama, M. and Okamoto, T. (1998). A mechanism for knowledge navigation in hyperspace with neural networks to support exploring activities. In *Proceedings of Current Trends and Applications of Artificial Intelligence in Education Workshop at the 4th World Congress on Expert Systems*, edited by G. Ayala, pp. 41–48. Mexico City: ITESM.

Keller, F. S. and Sherman, J. G. (1974). *The Keller Plan Handbook*. Menlo Park, CA: W.A. Benjamin.

Klausmeier, H. J. (1975). IGE: an alternative form of schooling. In *Systems of Individualized Education*, edited by H. Talmage, pp. 48–83. Berkeley, CA: McCutchan.

Koedinger, K. R. and Anderson, J. R. (1998). Illustrating principled design: the early evolution of a cognitive tutor for algebra symbolization. *Interact. Learn. Environ.*, 5, 161–180.

Kulik, A. J. (1982). Individualized systems of instruction. In *Encyclopedia of Educational Research* 5th ed., edited by H. E. Mitzel, p. 2. New York: Macmillan.

Landa, L. N. (1976). *Instructional Regulation and Control*. Englewood Cliffs, NJ: Educational Technology Publications.*

Lesgold, A. (2001). The nature and methods of learning by doing. *Am. Psychol.*, 56(11), 964–973.*

Lesgold, A. M., Lajoie, S. P., Bunzo, M., and Eggan, G. (1992). SHERLOCK: a coached practice environment for an electronics troubleshooting job. In *Computer Assisted Instruction and Intelligent Tutoring Systems: Shared Issues and Complementary Approaches*, edited by J. Larkin and R. Chabay, pp. 201–238. Hillsdale, NJ: Lawrence Erlbaum Associates.

Lester, J. C., Towns, S. G., and Fitzgerald, P. J. (1999). Achieving affective impact: visual emotive communication in lifelike pedagogical agents. *Int. J. Artif. Intell. Educ.*, 10(3–4), 278–291.

Leutner, D. (2004). Instructional design principles for adaptivity in open learning environments. In *Curriculum*, *Plans, and Processes in Instructional Design*, edited by N. M. Seel and S. Dijkstra, pp. 289–307. Mahwah, NJ: Lawrence Erlbaum Associates.*

Luckin R. and du Boulay B. (1999). Ecolab: the development and evaluation of a Vygotskian design framework. *Int. J. Artif. Intell. Educ.*, 10, 198–220.

Maki, H. R. and Maki, S. W. (2002). Multimedia comprehension skill predicts differential outcomes of Web-based and lecture courses. *J. Exp. Psychol. Appl.*, 8, 85–98.

Merrill, M. D. and Boutwell, R. C. (1973). Instructional development: methodology and research. In *Review of Research in Education*, edited by F. Kerlinger, pp. 95–131. Itasca, IL: Peacock.

Moore, A., Stewart, C. D., Martin, D., Brailsford, T. J., and Ashman, H. (2004). Links for Learning: Linking for an Adaptive Learning Environment. Paper presented at the Third IASTED Int. Conf. on Web-Based Education. February 16–18, Innsbruck, Austria (http://whurle.sourceforge.net/wbe04.pdf).

Ohlsson, S. (1987). Some principles of intelligent tutoring. In *Artificial Intelligence and Education*, edited by R. W. Lawler and M. Yazdani, pp. 203–237. Norwood, NJ: Ablex.

Ohlsson, S. (1993). Learning to do and learning to understand: a lesson and a challenge for cognitive modeling. In *Learning in Humans and Machines*, edited by P. Reimann and H. Spada, pp. 37–62. Oxford: Pergamon Press.*

Oppermann, R. (1994). Adaptively supported adaptability. *Int. J. Hum.-Comput. Stud.*, 40, 455–472.

Or-Bach, R. and van Joolingen, W. R. (2004). Designing adaptive interventions for online collaborative modeling. *Educ. Inform. Technol.*, 9, 355–375.

Park, O. (1996). Adaptive instructional systems. In *Handbook of Research on Educational Communications and Technology*, edited by D. H. Jonassen, pp. 634–664. New York: Macmillan.*

Park, O. and Lee, J. (2003). Adaptive instructional systems. In *Handbook of Research on Educational Communications and Technology*, 2nd ed., edited by D. H. Jonassen, pp. 651–684. Mahwah, NJ: Lawrence Erlbaum Associates.*

Park, O. and Seidel, R. J. (1989). A multidisciplinary model for development of intelligent computer-assisted instruction. *Educ. Technol. Res. Dev.*, 37, 72–80.

Park, O. and Tennyson, D. R. (1980). Adaptive design strategies for selecting number and presentation order of examples in coordinate concept acquisition. *J. Educ. Psychol.*, 72, 362–370.*

Park, O. and Tennyson, D. R. (1986). Computer-based response-sensitive design strategies for selecting presentation form and sequence of examples in learning of coordinate concepts. *J. Educ. Psychol.*, 78, 23–28.

Park, O., Perez, R. S., and Seidel, J. R. (1987). Intelligent CAI: old wine in new bottles or a new vintage? In *Artificial Intelligence and Instruction: Applications and Methods*, edited by G. Kearsley, pp. 11–45. Boston, MA: Addison-Wesley.

Peterson, L. P. (1977). Review of human characteristics and school learning. *Am. Educ. Res. J.*, 14, 73–79.

Peterson, P. L. and Janicki, T. C. (1979). Individual characteristics and children's learning in large-group and small-group approaches. *J. Educ. Psychol.*, 71, 677–687.

Peterson, P. L., Janicki, T. C., and Swing, S. (1981). Ability X treatment interaction effects on children's learning in large-group and small-group approaches. *Am. Educ. Res. J.*, 18, 453–473.

Quintana, C., Zhang, M., and Krajcik, J.(2005). A framework for supporting metacognitive aspects of online inquiry through software-based scaffolding. *Educ. Psychol.*, 40(4), 235–244.

Rebolledo Mendez, G., du Boulay, B., and Luckin, R. (2006). Motivating the Learner: An Empirical Evaluation. Paper presented at the 8th Int. Conf. on Intelligent Learning Systems, June 26–30, Jhongli, Taiwan (http://www.cogs.susx.ac.uk/users/bend/papers/ITS2006.pdf).

Reiser, A. R. (1987). Instructional technology: a history. In *Instructional Technology Foundations*, edited by R. M. Gagné, pp.11–48. Mahwah, NJ: Lawrence Erlbaum Associates.

Roll, I., Aleven, V., McLaren, B. M., Ryu, E., Baker, R., and Koedinger, K. R.(2006). The Help Tutor: Does Metacognitive Feedback Improve Students' Help-Seeking Actions, Skills and Learning? Paper presented at the 8th Int. Conf. on Intelligent Learning Systems, June 26–30, Jhongli, Taiwan (http://www.pitt.edu/~bmclaren/HelpTutor-ITS2006.pdf).

Ross, S. M. and Anand, F. (1986). Using Computer-Based Instruction to Personalize Math Learning Materials for Elementary School Children. Paper presented at the American Educational Research Association Annual Meeting, April, San Francisco, CA.

Ross, S. M. and Morrison, G. R. (1986). Adaptive instructional strategies for teaching rules in mathematics. *Educ. Commun. Technol. J.*, 30, 67–74.

Ross, S. M. and Morrison, G. R. (1988). Adapting instruction to learner performance and background variables. In *Instructional Designs for Microcomputer Courseware*, edited by D. H. Jonassen, pp. 227–243. Mahwah, NJ: Lawrence Erlbaum Associates.*

Ross, S. M. and Rakow, E. A. (1981). Learner control versus program control as adaptive strategies for selection of instructional support on math rules. *J. Educ. Psychol.*, 73, 745–753.

Rothen, W. and Tennyson, D. R. (1977). Pre-task and on-task adaptive design strategies for selecting number of instances in concept acquisition. *J. Educ. Psychol.*, 69, 586–592

Rothen, W. and Tennyson, D. R. (1978). Application of Bayes' theory in designing computer-based adaptive instructional strategies. *Educ. Psychol.*, 12, 317–323.

Scandura, J. M. (1977a). *Problem Solving: A Structural/Processes Approach with Instructional Implications*. New York: Academic Press.*

Scandura, J. M. (1977b). Structural approach to instructional problems. *Am. Psychol.*, 32, 33–53.

Scandura, J. M. (1983). Instructional strategies based on the structural learning theory. In *Instructional-Design Theories and Models: An Overview of Their Current Status*, edited by C. M. Reigeluth, pp. 213–249. Mahwah, NJ: Lawrence Erlbaum Associates.

Schwarz, E., Brusilovsky, P., and Weber, G. (1996). World Wide Intelligent Textbooks. Paper presented at the World Conference on Educational Telecommunications, June 1–22, Boston, MA (http://www.contrib.andrew.cmu.edu/~plb/ED-MEDIA-96.html).

Seidel, R. J. and Park, O. (1994). An historical perspective and a model for evaluation of intelligent tutoring systems. *J. Educ. Comput. Res.*, 10, 103–128.*

Seidel, R. J., Wagner, H., Rosenblatt, R. D., Hillelsohn, M. J., and Stelzer, J. (1978). Learner control of instructional sequencing within an adaptive tutorial CAI environment. *Instruct. Sci.*, 7, 37–80.

Seidel, R. J., Park, O., and Perez, R. (1989). Expertise of CAI: development requirements. *Comput. Hum. Behav.*, 4, 235–256.

Shapiro, A. M. and Niederhauser, D. (2004). Learning from hypertext: research issues and findings. In *Handbook of Research on Educational Communications and Technolog*y, 2nd ed., edited by D. H. Jonassen, pp. 605–620. Mahwah, NJ: Lawrence Erlbaum Associates.

Shute, V. J. and Psotka, J. (1996). Intelligent tutoring systems: past, present and future. In *Handbook of Research on Educational Communications and Technology*, edited by D. Jonassen, pp. 570–600. New York: Macmillan.*

Shute, V. J. and Towle, B. (2003). Adaptive e-learning. *Educ. Psychol.*, 38(2), 105–114.

Snow, E. R. (1980). Aptitude, learner control, and adaptive instruction. *Educ. Psychol.*, 15, 151–158.*

Snow, E. R. and Swanson, J. (1992). Instructional psychology: aptitude, adaptation, and assessment. *Annu. Rev. Psychol.*, 43, 583– 626.

Söller, A. L. (2001). Supporting social interaction in an intelligent collaborative learning system. *Int. J. Artif. Intell. Educ.*, 12, 40–62.

Söller, A. L., Martínez-Monés, A., Jermann, P., and Muehlenbrock, M. (2005). From mirroring to guiding: a review of state of the art technology for supporting collaborative learning. *Int. J. Artif. Intell. Educ.*, 15(4), 261–290.

Specht, M. and Oppermann, R. (1998). ACE: adaptive courseware environment. *New Rev. Hypermedia Multimedia*, 4, 141–161.

Steinacker, A., Seeberg, C., Rechenberger, K., Fischer, S., and Steinmetz, R. (1998). Dynamically Generated Tables of Contents as Guided Tours in Adaptive Hypermedia Systems. Paper presented at ED-MEDIA/EDTELECOM'99, 11th World Conf. on Educational Multimedia and Hypermedia and World Conf. on Educational Telecommunications, June 19–24, Seattle, WA (http://www.kom.e-technik.tu-darmstadt.de/publications/abstracts/SSR+99–1.html).

Steinberg, E. R. (1991). *Computer-Assisted Instruction: A Synthesis of Theory, Practice, and Technology.* Hillsdale, NJ: Lawrence Erlbaum Associates.

Suppes, P., Fletcher, J. D., and Zanottie, M. (1976). Models of individual trajectories in computer-assisted instruction for deaf students. *J. Educ. Psychol.*, 68, 117–127.

Tennyson, D. R. (1975). Adaptive instructional models for concept acquisition. *Educ. Technol.*, 15(4), 7–15.

Tennyson, R. D. and Christensen, D. L. (1988). MAIS: an intelligent learning system. In *Instructional Designs for Micro-Computer Courseware*, edited by D. Jonassen, pp. 247–274. Mahwah, NJ: Lawrence Erlbaum Associates.

Tennyson, R. D. and Park, O. (1987). Artificial intelligence and computer based learning. In *Instructional Technology: Foundations*, edited by R. M. Gagné, pp. 319–342. Mahwah, NJ: Lawrence Erlbaum Associates.

Thorndike, E. L. (1911). *Individuality.* Boston, MA: Houghton Mifflin.*

Tobias, S. (1976). Achievement-treatment interactions. *Rev. Educ. Res.*, 46, 61–74.

Tobias, S. (1987). Learner characteristics. In *Instructional Technology: Foundations*, edited by R. M. Gagné, pp. 207–231. Mahwah, NJ: Lawrence Erlbaum Associates.

Tobias, S. (1989). Another look at research on the adaptation of instruction to students characteristics. *Educ. Psychol.*, 24(3), 213–227.*

Tobias, S. (1994). Interest, prior knowledge, and learning. *Rev. Educ. Res.*, 64, 37–54.

van Merriënboer, J. (2005). Learners in a Changing Learning Landscape: Reflections from an Instructional Design Perspective. Paper presented at the Presidential Workshop and Panel Session at the International Convention of the Association for Educational Communications and Technology (AECT), October 18–22, Orlando, FL (http://www.learndev.org/dl/ibstpi-AECT2005–Merrienboer.pdf#search=%22Merrienboer%20mass-individualization%22).*

Vygotsky, L. (1978). *Mind in Society: The Development of Higher Psychological Processes*. Cambridge, MA: Harvard University Press.

Wang, M. (1980). Adaptive instruction: building on diversity. *Theory Pract*., 19, 122–128.*

Wang, M. and Lindvall, C. M. (1984). Individual differences and school learning environments. *Rev. Res. Educ*., 11, 161–225.

Wang, M., Oates, J., and Whiteshew, N. (1995). Effective school responses to student diversity in inner-city schools: a coordinated approach. *Educ. Urban Soc*., 27(4), 484–503.

Wasson, B. B. (1990). Determining the Focus of Instruction: Content Planning for Intelligent Tutoring Systems. Ph.D. thesis. Saskatchewan: Department of Computational Science, University of Saskatchewan.

Wenger, E. (1987). *Artificial Intelligence and Tutoring Systems: Computational and Cognitive Approaches to the Communication of Knowledge*. Los Altos, CA: Kaufmann.

White, B. Y., Shimoda, T. A., and Frederiksen, J. R. (1999). Enabling students to construct theories of collaborative inquiry and reflective learning: computer support for metacognitive development. *Int. J. Artif. Intell. Educ*., 10, 151–182.

Whitener, E. M. (1989). A meta-analytic review of the effect on learning of the interaction between prior achievement and instructional support. *Rev. Educ. Res*., 59, 65–86.

Williams, D. M. (1996). Learner-control and instructional technologies. In *Handbook of Research for Educational Communications and Technology*, edited by D.H. Jonassen, pp. 957–982. Mahwah, NJ: Lawrence Erlbaum Associates.

Wood, H. and Wood, D. J. (1996). Contingency in tutoring and learning. *Learn. Instruct*., 6(4), 391–398.

Wood, H. and Wood, D. J. (1999). Help seeking, learning and contingent tutoring. *Comput. Educ*., 33(2/3), 153–170.

Wood, H., Wood, D. J., and Marston, L. (1998). *A Computer-Based Assessment Approach to Whole Number Addition and Subtraction*, Technical Report No. 56. Nottingham, U.K.: Centre for Research in Development, Instruction and Training, University of Nottingham.

Zimmerman, B. J. and Tsikalas, K. E. (2005). Can computer-based learning environments (CBLEs) be used as self-regulatory tools to enhance learning? *Educ. Psychol*., 40(4), 267–271.

* Indicates a core reference.