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Contributions of Cognitive Psychology to the Future of E-Learning[1]

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At the beginning of the 21st century strong efforts are made for facilitating e-learning (electronic-based learning and teaching). This development is driven mainly by economical and technological dynamics, however also the contributions of educational and learning sciences are requested by the decision maker. Beside methodological contributions, cognitive psychology is fundamental for individualising e-learning processes. Essential for individualisation is the adaptivity of the e-learning system - comparable to the teaching behaviour of a private teacher, taking his or her knowledge about the student and the results of learning science into account. The theoretical models and empirical results of cognitive psychology enable us (a) to optimise the individual's learning of specific knowledge and skills by adapting the e-learning system to the student's pre-knowledge, to his or her growing knowledge and learning goal, and to the requested kind of comprehension and performance, (b) to optimise individual learning processes by adapting to or improving general learning skills, control processes and learning strategies, as e.g. the repeating schedule with respect to fast learning and long lasting retention, as the communication and co-operation activities, as the cognitive and learning style, and meta cognitive skills ("learning to learn"), and (c) to reduce other cognitive demands during the learning process by the systems adaptivity with respect to the student's cultural background, his or her human-computer-interface preferences as well as to changing learning environments. Realising these forms of adaptivity in e-learning systems by suitable objects of adaptivity on the appropriate level of individualisation of adaptivity needs interdisciplinary co-operation.

Key Words: e-learning, elearning, Web-based teaching (WBT), computer based training (CBT), individualisation, adaptivity, adaptive hypertext, knowledge spaces, applied cognitive psychology

1 Introduction

Currently, strong activities and efforts are made for facilitating electronic-based learning and teaching (e-learning). This development is primarily motivated by economical reasons and mainly driven by technological measures. However recently the officials for promoting research and development (R&D) noticed that developing new educational systems has to take into account the results of educational and learning sciences. In this article we focus on the contribution to e-learning of cognitive psychology as an important part of learning science.

Four or five years ago the term e-learning (e-Learning, E-Learning, eLearning, elearning) was not usable. Currently (September 24, 2001) the search engine "Fast Search" finds 243,504 pages for "e-learning" and 37,248 pages for "elearning". E-learning is the abbreviation for "electronic-based learning", the term has a broad meaning and captures terms like computer based learning and teaching, computer assisted learning, computer aided instruction, computer-based training (CBT), technology-based training, web-based training (WBT), internet-based training (IBT), internet-

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based learning (IBL), Web-based instruction (WBI), computer-assisted intelligent teaching system, intelligent tutorial system (ITS), intelligent computer-aided instruction (ICAI), interactive courseware. While a glossary on distance learning in 1998 does not mention e-learning at all, now different definitions are available. One of them defines e-lerning by "Education via the internet, network, or standalone computer. Network-enabled transfer of skills and knowledge. e-learning refers to using electronic applications and processes to learn. e-learning applications and processes include Web-based learning, computer-based learning, virtual classrooms, and digital collaboration. Content is delivered via the internet, intranet/extranet, audio or video tape, satellite TV, and CD-ROM."[i] Summarising important aspects, e-learning should give access to electronically based learning resources at anytime, anywhere, for anyone.

Furthermore, some of the definitions connect e-learning with e-business or e-commerce. The dynamic of e-learning business is driven by high turnover expectancies for the next years.

R&D (research and development) is focused on the aspects of information and communication technology (ICT), indicated by journals, proceedings, conferences, research programs and research grants. Also teaching in this field is primarily in the hands of computer scientists.

In this article we focus on the cognitive and learning science points of view including aspects of artificial intelligence and especially cognitive psychology.

2 Different views on the basic components of e-learning systems

Depending on the specific architecture, the level of abstraction and the point of view the basic components of an e-learning system may be described like this.

2.1 Computer technical point of view

Hard- and Software for

- Internet-services and -connectivity
- Server-clients interaction
- the operating systems
- input and output devices
- Human computer interfaces (HCI) including multimedia components
- browsing the Web giving access to distributed resources
- e-mail and newsgroup communication
- applications software

2.2 Artificial Intelligence point of view

- Knowledge Database
- Active Desktop
- Intelligent Search Engine
- Intelligent Agents

2.3 A service point of view

- Access Server
- e-Learning Server
- Training Track
- Testing Tool
- Attendance Tracking
- Certificate Server

2.4 An educational point of view

Learning objectives skills.
Meaningful interactions
Designed types of contact/interaction between the instructor and the student
Media elements: Text, audio, video, graphics/animations
Course management/Student assessment

2.5 The psychological point of view

Knowledge Base, contains the structured expert knowledge about the knowledge domain.

Student Model, represents the hypothetical knowledge state and other attributes of the student; the student model is the basis for adaptive pedagogical interventions, it has to be adapted to the learning progress, it may capture e.g. the students knowledge, mis-conceptions and general skills.

Teaching Model, decides about the pedagogical interventions taking into account the knowledge base and the student model.

Interactive Human Computer Interfaces, for presenting information to and receiving information from the student.

These four components are also called Domain Knowledge, Student Model, Tutor Model and User Interface (exercise dialogue, student feedback, system feedback).

Contributing to the development of e-learning systems as a psychologist primarily means to improve the four last components. Developing each of these components demands the theoretical and empirical results of cognitive psychology (see e.g. Mori 2001a, b, c).

3 Former contributions of psychology to e-learning

3.1 Programmed learning

Programmed learning is based on Skinnerian principles of operant conditioning. A programmed learning sequence helps a student to achieve a learning objective by breaking the information into a series of simple steps, presented sequentially and immediately "reinforced" (giving feedback). Programmed learning was popular in the sixties, it was finally successful only for drill learning and has been questioned like behaviourism in general for classroom pedagogy.

3.2 Mathematical models of rote learning

Mathematical models of rote learning assume that the learning progress is described either by incremental growth or by stepwise transitions between learning states. By individualised parameters for the difficulty of the learning tasks and the learning ability of the students the knowledge domain and the students are represented. The models have been developed in the fifties and sixties on the basis of Estes' Stimulus Sampling Theory or Bush and Mosteller's Linear Operator approach. 'Computer Assisted/Aided Instruction' (CAI) applications starting with language acquisition have been initiated by Richard Atkinson, a former influential memory and cognitive psychologist, now president of the University of California, and Patrick Suppes, who is one of the pioneers and leading figures in educational computer applications on the basis of psychology[ii] and he is still active in this field, e.g. by contributing to Stanford University's e-learning program for gifted youth (see below). The two pioneers co-founded the extremely successful company Computer Curriculum Corporation (CCC).

3.3 Cognitive modelling

Cognitive modelling has the aim to simulate the cognitive processes of humans by computers, e.g. the cognitive processes of storing information, solving problems, detecting inconsistencies, of meta cognitions. By so called 'Intelligent Tutorial Systems' (ITS) or 'Intelligent Computer Aided Instruction' (ICAI) these models have been used as student components in e-learning systems. Because the cognitive processes of the individual student are simulated, interventions of the teaching model can be derived and routed. Since the seventies, learning to program a computer language, to solve complex physical problems and so on have been modelled. Among others the working groups around John Anderson, Hans Spada, Karl Friedrich Wender should be mentioned. Almost all of these approaches until now are more or less only of academic value, while interesting results have been reached, many of them still remain theoretical and difficult to apply in the real world of broader field applications. However, in 1998 the Pittsburgh Advance Cognitive Tutoring Center has been founded by a group around John Anderson and their cognitive algebra tutor, originally developed at Carnegie Mellon University, has been successful applied in the field.

3.4 Knowledge Space Theory

The most recent psychological development in the field of e-learning is the Knowledge Space Theory (KST) founded in 1985 by Doignon and Falmagne. KST is a psychological mathematical theory (based on order and lattice theory) using dependencies between the problems and other learning objects in a knowledge domain for structuring the assessment process and the teaching process like a private teacher. Since 1985 the theory has been developed further by Doignon and Falmagne (1999), Koppen and Dowling, Albert and Lukus (1999) and others. Basic concepts of knowledge space theory are (a) prerequisite relationships between test items, problems or learning objects (b) the knowledge states of the students and their knowledge space and (c) sequences of knowledge states representing possible learning paths from the individual starting state to the selected goal state.

Recent applications are the Adaptive Tutorial Systems ALEKS[iii] and RATH[iv] in the fields of mathematics. ALEKS is a commercial product developed by Falmagne and his group with support of the US-based National Science Foundation, distributed and supported by the ALEKS company, while RATH is a prototype at the University of Graz.

4. Web-based e-learning systems

4.1 Psychological reasons for Web-based e-learning systems

The most advanced technology in e-learning is the internet. Also from psychological points of view Web-based e-learning systems are preferable. Why is cognitive psychology a strong partner in developing Web-based e-learning systems? The main methodological reasons are

* Applying empirical findings to structuring content, creating student models and teaching models.
* Theory-based models of learning, reasoning, problem solving, knowledge retrieval, remembering and retention which have been proven to be empirically valid.
* Methodology for creating and presenting learning objects.
* Clearly defined learning objects and strict control on learning objects.
* Clearly defined and specified (classes of) actions of the teaching system.
* Methodology for recording the students' data, their traces of learning behaviour.
* Methodology for collecting, analysing and interpreting behavioural data, which are not only answers to multiple choice questionnaires or solutions of problems, but also latencies, eye tracking data, movements e.g. of the computer mouse, video recordings, as well as psycho-physiological data.
* Expertise in computer-based and Web-based experimental methodology for assessing and shaping behaviour and the processes and structures behind the behaviour - no other discipline offers this.
* World wide collection of data and information for testing the psychological and educational models or theories of teaching and improving or refining the e-learning systems.

4.2 Examples of Web-based e-learning systems

Interactive linear tutorial

Vector Math for 3D Computer Graphics. An Interactive Tutorial[v]

This course of B. Kjell (Central Connecticut State University) with 16 chapters is structured linearly. Each chapter consist of a short lessen, a question and the right answer. The tutor is student driven, the student can navigate forward and backward.

Interactive, adaptive, and integrated course

ALEKS: Math Tutor[vi]

The adaptive tutorial system has been developed by Falmagne at the University of California at Irvine, now offered by ALEKS Corporation, it is based on Knowledge Space Theory. This non linear tutor starts with assessing a new student's knowledge and after that presenting and offering lessons, problems etc. According to the student's changing knowledge, the tutor is adaptive, i.e. the tutor presents learning objects the student is able to understand.

RATH Relational Adaptive Tutoring Hypertext WWW-Environment[vii]

The system is a prototype, developed in co-operation with the first author by Cord Hockemeyer at University of Graz, it is also based on Knowledge Space Theory. Actually the system presents elementary probability contents as lessons, examples and exercises. The student has access to those learning objects he or she is able to understand. Principles for structuring domains and testing the validity of the derived knowledge structures together with modern technology of link-hiding have been used for creating the prototype RATH.

Whole curriculum

Education Program for Gifted Youth[viii] (EPGY)

The program is offered by the Stanford University and contains e-learning courses for the gifted and talented students. EPGY provides the students with an individualised educational experience. Students have access to courses in a variety of subjects at levels ranging from kindergarten through advanced-undergraduate. The e-learning courses consist of multimedia lectures utilising voice accompanied by synchronised graphics, capturing the informal nature of classroom instruction, while preserving a level of rigor appropriate to the subject matter. In some courses lectures are followed by interactive exercises in which answers are evaluated by the computer. Off-line work includes traditional textbook reading assignments and exercises. For tutorial support, students can attend help-sessions with an instructor and other students in an internet-based virtual classroom. Teaching assistants are available for internet-based virtual office hours, by e-mail, and by a toll-free telephone line.

Whole company

Computer Curriculum Corporation - NCS Learn[ix]

The company which changed its name recently offers a wide range of courses and software as well for the classroom and web-based learning. The company is one of the oldest provider of e-learning. It's development from providing systems for classroom teaching to web-based teaching systems, which does not necessarily depend on the classroom environment, is well documented in the internet.

5 Individualisation and adaptivity

Since the sixties computers are used in classrooms. Still nowadays, technology oriented educational applications focus on the classroom. Developing technology in education for classroom teaching still is a hot topic; e-learning is viewed a special tool supplementing classroom teaching (see e.g. Bransford et. al., 2000; Sandholtz et al. 1997) .

Research however already has the aim to make the e-learning system behaving like a private teacher. A private teacher has only one student at a time and can adapt his or her teaching behaviour to the individual student, to the student's learning state, his or her abilities, needs and so on, using his knowledge about the student. However the private teacher is not only using the knowledge about the individual student but also about the theories, results, methods, procedures and techniques of learning science. The key concept for implementing individualised teaching into e-learning systems is the system's adaptivity.

By far the most important topic in current e-learning research is adaptivity. Adaptive hypermedia systems bridge the gap between technology driven tutoring systems (risk: mental overload, de-motivation) and student driven learning environments (risk: lost in hyperspace).

In accordance with contributions of the first author together with Cord Hockemeyer to the "Requirements Specification" document of the EC-funded EASEL-project[x], we distinguish between the direction or objective of adaptivity, the objects of adaptivity and the level of individualisation of adaptivity

5.1 Directions and objectives of adaptivity

The objectives of adaptivity include among others the adaptivity to the requirements of different learning cultures, to the teacher's and the student's aims and goals, to the student's cultural background, to their preferences in human computer interaction, to their communication style and communication needs, to their cognitive and learning style, to their actual (pre)knowledge, learning history and expertise.

5.2 Objects of adaptivity

The question, what is to be adapted in an e-learning system, is strongly related to the objectives of adaptation. Candidates for objects of adaptivity are among others adaptivity of navigation (e.g. dynamically generated learning paths), navigation support methods, the documents' inner structure and the kind of presentation, documents' granularity, courses contents and their structure. The objects of adaptivity have to be adaptive themselves and to adapt to the individual because human behaviour, including learning, depends on the individual as well as the situational context.

5.3 Level of individualisation of adaptivity

Depending on the learning culture, the status of technology, and the status of research the level of individualisation of adaptivity can differ. In some cultures, a high amount of standardisation is requested. Group level adaptivity is common for subgroups or minorities in a culture, including e.g. special needs and gender. Individual level is aimed at in western cultures with the model of private teaching in behind. However in many cases the actual status of learning science allows only group level adaptivity. If e.g. the scientific results are merely on the level of comparing the behavioural effects of two conditions (e.g. two mnemonic strategies) for two groups of people (e.g. high vs. low imagination ability) the amount of individualisation can be realised only on the group level. At the other extreme, in case of a empirical valid psychological mathematical model, which maps as well individual and situational differences into the model structure or the parameter space, the adaptive process can be totally individualised. In cognitive psychology mathematical models of knowledge representation (see e.g. Albert, 1994) and of memory (see e.g. Neath, 1998, and Neath, Models of Memory, http://rumpole.psych.purdue.edu/models/) are available which can be used in e-learning systems for adapting to the individual student.

6 Optimising the objectives of adaptivity

Learning is an adaptive process, the interactive e-learning system has to support this process by being adaptive itself. In optimising this kind of support we start our considerations with widely accepted assumptions about mental processes and cognition. Since the 19th century's contribution to cognitive psychology it is known that the human mind has limited information processing capacity of the so called working memory. Müller and Pilzecker called this the "Enge des Bewusstseins" (narrowness of consciousness). More or less at the same time William James distinguished between two functional kinds of memories, the primary (working memory) and the secondary memory, today called long term memory, semantic memory, or knowledge (declarative and procedural knowledge). Since Atkinson and Shiffrin's modelling of rehearsal processes it is widely accepted that the flow of mental information is regulated by control processes, as well top down as bottom up processes. Rehearsal processes, goal setting etc. are of the first kind, while e.g. cue dependent activation of knowledge is of the second kind. On the background of this theorising, supporting the student's learning process by optimising the objectives of adaptivity means that (1) the intended individual learning of the specific knowledge and skills according to the learning aims and goals has to be optimised and (2) the control processes and general skills have to be optimised while (3) other cognitive demands have to be minimised taking into account limited cognitive processing capacity and time constraints.

6.1 Optimising the learning of specific knowledge and skills

Adapting to the student's pre-knowledge

With a knowledge domain structured by prerequisite relationships according to Knowledge Space Theory an adaptive assessment of the students pre-knowledge state can be performed by the system. The assessment procedure itself is adaptive, realised by answer- and performance-dependent exposition of the next test item and by drawing conclusions for other items, which do not have to be presented necessarily. It is widely accepted that taking the pre-knowledge into account enables the student to understand, to connect new information with existing knowledge, to use metaphors and analogies, to be and to feel neither overburdened nor underburdened.

Optimising learning by adapting to the student's/teacher's learning aims and goals

For a knowledge domain structured according to KST the learning goal is defined by the knowledge state which has to be reached by the student. A system adapts by directing the student towards those contents which are in accordance with the specified goal. Adjusting to the goal has to be observable, directly (performance oriented) or indirectly (competency oriented).

Optimising learning by adapting to the student's actual knowledge

The actual knowledge of a student is represented by her or his knowledge state. Depending on the actual knowledge, the learning objects made accessible to the student are determined applying meta data about the prerequisite relationships between the available learning objects and the knowledge which is necessary for comprehension. Thus the student is neither overburdened nor underburdened. Systems providing such kind of adaptivity based on the KST are the ALEKS system and the RATH system.

Choosing the kind of knowledge level and optimising test and instructional events

Doignon and Falmagne's approach is purely behavioural by only demanding, that performing and achieving a knowledge state has to be observable. From a cognitive point of view the aspect of observable states is necessary however not sufficient. Definition of pre-knowledge state, goal specification and actual knowledge state can be of different knowledge level, e.g.

* choosing a difficulty level by recognition, recalling, transferring or problem solving demands,
* selecting different types of tasks like application, examples, investigation, theorising, or
* defining the state only by performances or also by competencies and conceptual knowledge or even misconceptions.

Concluded from the model of information processing combined with Knowledge Space Theory, one of the most important factors in optimising learning objects are their relationships to the other learning objects, their inner structure and the relationship to the students knowledge; thus also knowledge (analogies, metaphors, structural similarity etc.) which mediates learning object content to knowledge stored in semantic memory has to be taken into account, furthermore the learning or cognitive styles (see below).

One important aspect in creating learning objects is Craik and Lockhart's levels of processing approach with tasks demanding deeper, semantic processing resulting in better comprehension, storage, and retention.

6.2 Optimisation of the control processes, general skills and learning strategies

Optimising the control processes on the one end means to guide the student as far as possible in order to avoid information over load. On the other side it means to equip the e-learning system with adaptive tutorial elements enabling the student to improve his control strategies systematically. This whole spectrum can be applied on each of the following control processes.

Optimising speed of learning and duration of retention

Guiding the student during the acquisition of new knowledge aiming not only at effective learning but also at long term retention. The models and results of memory psychology referring to massed and distributed practice and to life long retention can be used for individual guidance.

Optimising by refreshment

Weeks, months and years after new learning, an-other aim may be to signal the individual student on activities to avoid forgetting of prior knowledge and skills. The models and results of memory psychology in the field of forgetting and retention are the basis for the system's individual guidance.

Optimising learning by communication, co-operation and collaboration

The e-learning system should support different types of co-operation and collaboration strategies for improving comprehension and learning. Based on Knowledge Space Theory and some preliminary work of Hoppe and Okamoto & Inaba the collaborative RATH, called CRATH has created and will be available for the public end of 2001. The basic idea is that the selection of partners for peer tutoring is guided depending on the relationship between the knowledge states of the student and possible tutors. As already mentioned, world-wide online and offline communication allows for new forms of collaboration in learning and teaching. Beside implementing supporting systems like the KST-based CRATH, the question arises whether it should be an aim in general, to facilitate the learning of learning-related communication, co-operation and collaboration skills. In that case the e-learning system has to have an adaptive component which shapes the students communicative skills individually.

Student's cognitive and learning style

One of the most popular hot topics in applied cognitive psychology since more than 100 years is the cognitive and learning style. In it's simple form, only the student's most preferred way of presenting learning material, e.g. visual, textual, or auditive, is taken into account. The multiple coding and multiple storage theories of memory research suggest however a more sophisticated form of adaptivity, which has to be shown empirically valid in an ecological setting by e.g. Mayer (2001).

Meta cognition and learning strategies

More general concepts of cognitive and learning styles have been published, e.g. holistic vs. analytic style, short term vs. long term planning. The focus was on the assessment of these hypothesised styles.

Basic research on meta cognition found substantial effects on achievement and performance, and may be the foundation, the theoretical basis for the long lasting experiences with "learning how to learn"-effects. Thus, again the question arises, shall an e-learning system adapt to the learning style of a student or shall almost each system try to optimise the student's meta-cognitive and strategic learning ability and behaviour.

Curriculum development and instructional design

Based on Knowledge Space Theory and prerequisite relationships an extension has been introduced, which allows to formalise the relationship between different tests and different courses. This can be the basis for developing a computer-based tool which allows to develop and to (re)structure knowledge assessments and curricula.

Prerequisite relationships can be investigated between courses as well as between single items and learning objects. Thus (re)structuring within and between courses is possible. The planned tools will support ordering courses within a curriculum, completing courses with existing contents which are needed as prerequisites but are assumed to be learned in earlier courses, or restructuring a whole curriculum into courses.

6.3 Optimising by minimising other cognitive demands

Preliminary remark

Minimising the demands which are not necessary for the learning process, of course, depends on the learning domain and the to be specified aims and goals of the learning process. If for instance beside the explicit aim of learning for an immigrant, living in an other country, the implicit learning of cultural values of the hosting country is also intended, the system should not adapt to the student's cultural background by minimising the demands, but by optimising them.

Minimising demands by adapting to the student's cultural background

Adapting to the cultural background of a student seems to be a simple affair, at first sight, by taking into account

- his or her native language, e.g. Japanese
- familiar measures and weights, e.g. Yen
- specific ways of writing things, e.g. marking on a form sheet by a circle (instead e.g. of a "X", which is common in the German culture for marking, this X-symbol has however an opposite meaning in Japan)
- well known brands, persons, or incidents, and so on.

However, the person may have migrated as a child, or the learner still is a child, with restricted language abilities. In a global world of teaching and learning many attractive e-learning systems will be provided in English, the students however may use English as a second language with restricted ability. Even in the same country different cultural backgrounds may exist, e.g. it is common sense in gender research, that the cultures of women and men are different. Even in these cases the system should adapt to the person's background and ability individually.

Minimising demands by adapting the human-computer interface to the user

In e-learning human-computer interfaces with a minimum of cognitive and physical demands are necessary. In the future de facto standards will be established. However individual preferences have to be taken into account by adaptive properties of the system. The current solution is, that the student adapts the system to him- or herself through option- or preferences-menus. Furthermore, the student always can choose between, on the one side, selecting between menus and their options (recognition) and, on the other side, a command language input into the system (recall). The adaptivity performed by the student however can not be the solution for e.g. handicapped students with their special individual needs which may be restricted in selecting or even need special input and output devices.

Minimising the teacher's demands by adapting to the requirements of different learning cultures

Until now our considerations have been student centred. However the contents, structures etc. have to be adapted also to the requirements given from outside, often connected with formal or technical demands. Examples are existing curricula which may be pre-defined by public authorities, or the technical equipment available in a certain learning environment. This kind of adaptivity has itself to be adaptive because of newly gained knowledge, technology, and a changing educational policy has to be handled.

7 Concluding remarks

For individualised adaptive teaching the usage of valid models from cognitive psychology is absolutely essential. However there are some necessary preconditions cognitive psychology has to demand on. First of all the teaching in psychology is involved which avoids to use precisely formulated models, which does not take into account modern information and communication technology as a professional standard, and does not prepare for interdisciplinary co-operation. On the other side, the self awareness of psychologists often does not correspond to the high level of expertise, which may result in avoiding interdisciplinary co-operation. Creating however the e-learning system of the future needs collaboration between different disciplines like psychology, artificial intelligence research, educational and learning sciences, computer science, linguistics, and philosophy. In Europe the European research funding societies offer an excellent framework for co-operation, which for instance the first author uses in the EASEL-project (for more information http://wundt.uni-graz.at and http://www.fdgroup.co.uk/easel). In Japan the conditions for co-operation are excellent because of strong groups for instance in cognitive psychology, artificial intelligence, natural language processing and a distributed research landscape which involves the government, the academia, the industry and the customer, i.e. the teacher and the students.

References

Albert, D. (Ed.) (1994) *Knowledge Structures*. Berlin, Heidelberg, New York: Springer-Verlag

Albert, D. & Lukas, J. (Ed.) (1999) *Knowledge Spaces. Theories, Empirical Research, and Applications*. Mahwah, New Jersey: Lawrence Erlbaum Associates, Publishers.

Bransford, J. D., Brown, A.L. & Cocking, R. R. (Ed.) (2000) *How People Learn. Brain, Mind, Experience, and School*. Expanded Edition. Washington, D. C.: National Academy Press. (The volume is also available online at http://www.nap.edu)

Doignon, J.-P. & Falmagne, J.-C. (1999) *Knowledge Spaces*. Berlin, Heidelberg, New York: Springer-Verlag.

Mayer, R. E. (2001) *Multimedia learning*. New York: Cambridge University Press.

Mori, T. (Ed.) (2001a) *The Exciting Lab of Language* (in Japanese). Kyoto : Kitaoji Shobo.

Mori, T. (Ed.) (2001b) *The Exciting Lab of Memory* (in Japanese). Kyoto : Kitaoji Shobo.

Mori, T. (Ed.) (2001c) *The Exciting Lab of Thinking* (in Japanese). Kyoto : Kitaoji Shobo.

Neath, I. (1998) *Human Memory. An Introduction to Research, Data, and Theory*. Pacific Grove, California: Brooks/Cole Publishing Company.

Sandholtz, J. H., Ringstaff, C. & Dwyer, D. C. (1997) *Teaching with Technology: Creating Student-Centered Classrooms*. New York: Teachers College Press, Columbia University.

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[i] Lernframe Co. (2001) About e-learning. Glossary of e-Learning terms. [WWW document] Retrieved September 28, 2001 from http://www.learnframe.com/aboutelearning/glossary.asp.

[ii] Suppes, P. (n.d.) Papers on Computers and Education. [WWW document] Retrieved September 24, 2001 from http://www.stanford.edu/~psuppes/education.html.

[iii] ALEKS Corporation (2001) ALEKS A better state of Knowledge. [WWW adaptive tutor] Retrieved September 27, 2001 from http://www.aleks.com/.

[iv] Hockemeyer, C. (n.d.) RATH Relational Adaptive Tutoring Hypertext WWW-Environment. Version 0.11 Prototype. [WWW adaptive tutor] Retrieved September 27, 2001 from http://wundt.uni-graz.at.

[v] Kjell, B. (July 2000) Vector Math for 3D Computer Graphics. An Interactive Tutorial. Second Revision. [WWW interactive tutorial] Retrieved September 28, 2001 from http://chortle.ccsu.ctstateu.edu/VectorLessons/vectorIndex.html.

[vi] ALEKS Corporation (2001) ALEKS A BETTER STATE OF KNOWLEDGE. [WWW adaptive tutor] Retrieved September 27, 2001 from http://www.aleks.com/.

[vii] Hockemeyer, C. (n.d.) RATH Relational Adaptive Tutoring Hypertext WWW-Environment.Version 0.11 Prototype. [WWW adaptive tutor] Retrieved September 27, 2001 from http://wundt.uni-graz.at.

[viii] Stanford University (n.d.) Education Programm for Gifted Youth (EPGY), e-learning courses for the gifted and talented students. [WWW documents] Retrieved September 27, 2001 from http://epgy.stanford.edu/.

[ix] NCS Learn.(n.d.) [WWW documents] Retrieved September 27, 2001 from http://www.cccpp.com/ and http://www.ncslearn.com.

[x] EASEL, Educator Access to Services in the Electronic Landscape. [WWW documents] Retrieved September 27, 2001 from http://www.fdgroup.com/easel/.