FLEXIBLE SOFTWARE DESIGN

SOFTWARE TO ACCOMMODATE INDIVIDUAL LEARNING DIFFERENCES

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MOTIVATION FOR THIS PAPER

Individual differences in perception, motivation and cognition influence what we learn, how we learn, and how long it takes to learn. Individuals differ in their degree of engagement, ability to focus, and in their capacity to remember, read, and do math. They differ, further, in prior experiences, skills, and knowledge. This strongly influences what students see, attend to, retain, and retrieve. The most practical way to provide the flexibility required to customize learning materials to individual differences is to use computer-based materials (Buelow, 2003; D. Rose & A. Meyer, 2002; Tinker, 2001).

This paper describes the requirements for a software architecture that provides the flexibility needed to customize computer-based instruction to individual needs. We are interested specifically in software-only approaches to the flexibility needed because software can be widely distributed. We are particularly interested in teaching fundamental concepts in mathematics and science at the secondary and college levels. The topics taught at these levels raise difficulties because of the abstract and mathematical nature of the subjects. Not only is the content challenging, but the preferred instructional style uses guided exploration. Finally, we want to ensure that flexible software is provided for two areas in which software makes major contributions to math and science learning: using probeware and computational models.

Equity Concerns

The ideal environment for customized materials requires that each student have access to a personal portable computer: personal so it can be individualized, and portable so it can be used anywhere. While this may appear to present an equity challenge by favoring students on the affluent side of the "digital divide," five years ago, it became clear to experts (Noll, 2001; Pea, 2001) that the digital divide was more an issue of how computers were used than whether they were available. Student access to personal computers is the norm at the college level where four years ago 85% of students owned computers (Jones & Madden, 2002) and is increasingly common at the secondary level (Newburger, 2001). For instance, Cobb County (GA) Schools were able to purchase 64,000 iBook computers at $271 each for every secondary student (Cobb County School District, 2005; Zucker, 2005).

The digital divide issue is not one of equity of access but of equity of usage. Poorer schools tend to use lower-quality applications (Dickard, Honey, & Wilhelm, 2003) and make less use of the kinds of applications such as science models and tools that are associated with increased student performance (National Center for Education Statistics, 2000). Research that contributes to a better understanding of how to use technology more productively is needed to address this aspect of the digital divide. Thus, the present is the perfect time to focus on customization; soon there will be ample computers to take advantage of customization, even in the poorest schools.

SOURCES OF RECOMMENDATIONS

The dream of tailoring learning materials to individual differences is an old one. As individual learning differences have been identified and codified into cognitive or learning styles (e.g., Kolb, 1976, 1984), or multiple intelligences (e.g., H. Gardner, 1985; H. Gardner, 1991), there have been extensive debates about the power and stability of these constructs (Laurillard, 2002; Pask, 1976), and the advisability of teaching and testing to them (Huber, 1983).

Now several sources of recommendations are converging with similar software design features that can help match learning tasks more effectively to individual capabilities and to the nature of particular tasks. These include several strands of cognitive psychology research, educators advocating Universal Design for Learning (UDL), and accessibility requirements that address students with special needs. The remarkable point is that all these strands converge around common ways of making software more flexible.

COGNITIVE SCIENCE RESEARCH

Overview of Relevant Research

An important strand of cognitive science research concentrates primarily on inputs to the brain, and less on the more difficult question concerning what happens in the brain. Researchers in this area tend to describe knowledge in terms of schema that can be used, but not how schema are created, linked, and extended. This is primarily a problem of measurement; these researchers have learned how to estimate input processing load and the rate of acquisition of simple schemas. Other strands of research are more focused on mental processing but this research cannot yet provide guidance on how to adapt software to the cognitive processing strengths and weaknesses of individual students.

Some of the research cited below may not be as general as it appears, because it was conducted in "training" contexts in which the instructional style was "telling", and the assessment was based on recall. Also, most of the research was conducted on small numbers of similar learners. Therefore, as in all educational research, caution must be exercised in applying these conclusions in new learning contexts. Our stance is to look through the literature for clues that might guide personalization and then to test the resulting software in our learning contexts.

Cognitive Load Theory. This strand of research is based on a model in which sensory information enters the brain in such a way that visual and audio information follow their own tracks (Baddeley, 1986; Clark & Paivio, 1991; Paivio, 1986). When this information arrives in working memory – a short-term processing region of limited capacity (Miller, 1956) – associations are found and linked. Long-term memory then stores the information in huge numbers of schemas (Chi, Glaser, & Rees, 1982). Once in long-term memory, schemas, which can be treated as individual associations (Shiffrin & Schneider, 1977), can be accessed by working memory with varying degrees of automaticity (Kotovsky, Hayes, & Simon, 1985). A wide range of experiments have found that working memory can be overloaded, leading to the idea of limited cognitive load (e.g., Baddeley, 1992; Chandler & Sweller, 1991; Sweller, 1988; Sweller & Chandler, 1991, 1994).

Multimedia Theory. Multimedia learning represents a related strand of research that looks at the simultaneous processing of images and sounds. Learning with multimedia has been defined as building mental representations from pictures or animations and text. Mayer (e.g., Mayer, 2001, 2003) and Mayer and Morino (2003) have found that complementary presentations of words and pictures increase learning efficacy. Strategies for overcoming the limitations of working memory have been recommended, e.g., signaling key ideas, segmenting longer processes, removing extraneous material, and presenting words and pictures close to one another.

Recommendations from Cognitive Research

In the following, this research is summarized as a series of design suggestions that might be helpful in the design of exploratory computer-based learning environments. In assembling this collection, we have selected results that appear to lend themselves to software features that could be customized.

1. Use both audio and visual channels. The simultaneous use of both auditory and visual inputs appears to reduce the load on working memory, as the visual and audio channels are independent, and may provide their own preliminary integration of information. The best use of this capacity is to provide different but related information in visual and audio form.

Provide audio. Having the computer speak text significantly improved some students' performance (Rose & Meyer, 2000; D. Rose & A. Meyer, 2002). Mousavi et al (1995) and Tindall-Ford et al. (1997) demonstrated superior learning when texts were presented as audio rather than text.

Use both channels at the same time. Studies have found that audio narrative added substantially to learning when delivered close to pictures, and did not help when delivered sequentially (R. E. Mayer & R. Anderson, 1992; Mayer & Moreno, 1998; Moreno & Mayer, 1999a; Tindall-Ford et al., 1997).

Don't just read the text. The audio channel should not just duplicate text. Auditory inputs do not necessarily improve learning. Tabbers, Martens, & van Merrienboer (2000) failed to find a value in audio inputs. Moreno and Mayer (2001b) found that simultaneous narration text and animation at times overloaded subjects.

Keep the audio short. Studies have also found that audio narrative added substantially to learning when delivered close in time to pictures, but not when delivered over a long period, when the user was unable to "skim" (R. E. Mayer & R. B. Anderson, 1992; Mayer & Moreno, 1998; Mayer & Moreno, 2003; Tindall-Ford et al., 1997)

2. Reduce unnecessary processing. A great deal of time and effort is required if the student must make unnecessary searches of extraneous information that is not germane to the task at hand. It is important that instructional materials be presented in ways that reduce cognitive load and allow the user to focus on the appropriate learning areas of schema-building (Chandler & Sweller, 1991).

Don't expect beginners to profit from open-ended inquiry. Researchers have found that asking students to solve a problem given an unstructured creates cognitive load (Mawer & Sweller, 1982; Sweller, 1983, 1988; Sweller & Levine, 1982; Sweller, Mawer, & Howe, 1982).

Start with partially worked examples. Researchers found that partially or fully worked examples were not only a better way to learn problem-solving than conventional teaching strategies, but also superior to discovery/inquiry strategies (e.g. Paas & van Merrienboer, 1994b; Sweller & Cooper, 1985).

Reduce redundancy. While it might seem that redundant materials would increase learning, "removing the redundant on-screen text provides the best learning conditions by preventing students' visual working memory from becoming overloaded" (Moreno, 2001a; Moreno & Mayer, 1999a, 1999b).

Eliminate screens that split attention between parts. Using both text and illustrations can split student attention, requiring wasteful searches. One strategy for reducing split attention is placing text inside pictures (Bodemer, Ploetzner, Feuerlein, & Spada, 2004; Moreno & Mayer, 1999a).

Put text close to images. Mayer (1991; 2003; 1992; 1996) notes that it matters that words and pictures be placed closely together (though not always simultaneously) – a "spatial contiguity effect".

Color-code text and illustrations. In another study (Kalyuga, Chandler, & Sweller, 1999), color-coding was used to link the text with corresponding parts of a picture, preventing unnecessary visual search and lowering cognitive load.

Don't use too much color. The number of features per object (e.g., color) matters in visual short-term memory (Olsen & Jiang, 2002).

Simplify screen designs. Field dependent students may be more successful with simpler arrays of elements. Lowe (2004) notes that students expend significant mental energy limiting aspects of animations to which they attend. Technology offers users a way to control the level of complexity in the learning environment by allowing users to remove extraneous or redundant material (Mayer & Moreno, 2003; Palmquist & Kim, 2000).

Avoid visual elements that are distracting. Lowe (2004) notes that students expend significant mental energy limiting what aspects of animations to attend to. He has begun to look at the way students integrate across visual regions. Learners, not surprisingly, tend to limit their interrogations in time and space, focusing on the most visually salient features, but missing the larger picture.

Serialize. Graphs, tables, formulae, and text are all critical to learning of science, and in many situations, simultaneous representations are necessary. Students are easily overwhelmed by screens with too many representations (Kozma & Russell, 2005). There should be options for using only screens of less complexity, such as allowing students to sequence through multiple screens serially instead of attempting to put everything on one screen.

3. Allow the learner to anticipate inputs. The amount of information being processed can be reduced if the learner perceives the information in meaningful schema. The more schema recall is automated, the less likely new information will overload working memory. Research indicates various ways of telling a learner in advance what is to be learned.

Orient students prior to starting an activity. Priming users before beginning an activity may help them group information to reduce load. For instance, students need preparation for observing a model (Sims, 1999), including orientation to the model space and the setting of controls for pacing and other factors.

Set expectations. Priming for a model-based activity requires more than becoming acquainted with the environment; students must have some idea of what content they will view in order to see it, and be able to make predictions about relationships among objects (van Joolingen & de Jong, 1991).

Overview/concept maps or drawings are useful for learners who need to see the whole picture before delving into detail, whereas others may need to see a logical, step-by-step exposition and may need aids for description and procedure building (Ford, Wood, & Walsh, 1994).

Re-use environments. Students become more comfortable over time with some multimedia (Vollmeyer, Burns, & Holyoak, 1998), probably because they are able to anticipate that they will see and the controls they will use, thus reducing load.

Use text to annotate visual images. Mayer and colleagues report that images are powerful adjuncts to textbook readings, sometimes even replacing the need for extensive reading (Mayer, 1989a; Mayer et al., 1996; Mayer & Gallini, 1990). Yet in some cases, the presence of additional (non-annotation) text decreased learning. The annotated images approach, on the other hand, was effective. It could be that the annotations help the student focus on relevant parts of an illustration, or indicate what to see in the illustration.

Give expert students open-ended explorations. The schemas that are available to a learner can influence whether means-ends problem solving creates excessive cognitive load. "If the schema for the area is known, the exploration or discovery method may be as beneficial as the worked examples approach. However, if the schema are poorly known, the exploration or discovery approach is more time consuming and the learning is less effective than the worked examples approach for high element interactivity material" (Tuovinen, 2003).

4. Increase the rate of feedback. Interactivity that provides rapid and meaningful feedback can decrease cognitive load and increase the rate and accuracy of schema acquisition. In general, students learn better where there is more interactivity (Mayer & Chandler, 2001). While it is important to distinguish between kinds of interactivity (e.g. Ellis, 2004) and a number of typologies have been suggested to do so (Fenrich, 1997; Hannafin, 1989; Kristof & Satran, 1995), it is the accessibility and relevance that matters most from a cognitive perspective.

Interactivity. "Interactivity" has many meanings from a narrow definition of clicking to active work with learning material, such as dialoguing and writing summaries. In general, students learn better where there is more interactivity (Mayer & Chandler, 2001). Interactivity that provides rapid and meaningful feedback can decrease cognitive load and increase the rate and accuracy of schema acquisition.

Give students control of parameters. Giving students controls can provide useful feedback, particularly if students can systematically vary one variable at a time (e.g. Tschirgi, 1980), allowing them to isolate the effect of each variable independently, and thereby identify rules (Klahr, Fay, & Dunbar, 1993).

Give students rate control. Students may need to alter the rate and direction of presentation (Schwan & Riempp, 2004) or aspects of layout and design. Schwan and Riempp found that giving users rate and direction interactivity did not affect user time on task, but resulted in notable difference in learning success.

5. Personalize the interactions. Students learn better when they are more engaged. Strategies for engagement with models and tools include interactivity and personalization.

Allow students to assume a role. Students who learned in a participatory agent-based environment remembered more, were better able to solve far transfer problems, and rated the activity more favorably than students who learned in a non-participatory agent-based environment (@missing). In MW, this could be accomplished by having students "be" and atom, set the rules it obeys, follow it visually, and hear its collisions.

Make the experience personal. Encouraging students to encode the lesson as a personal experience facilitates the processing of the content by making available experiences in memory to which the lesson can be related. "Students who learn with the voice of an agent rate the lesson more favorably, recall more, and are better able to use what they have learned to solve problems than students who learn the same verbal materials as on-screen text" (Moreno & Mayer, 2000).

Encourage group discussions. When studying student learning with system dynamics, Spector and Davidsen (2000) found that most learning appears to happen in the small group discussions and not in the direct interactions with the simulation model. Here social motivation may pair with the power of audition in learning.

Use informal style. Words, whether spoken or in text, should be presented in informal rather than formal style – a "personalization effect" (Moreno & Mayer, 2000).

Allow control of screen design. Because complex models often require screens that contain multiple displays, their color, intensity, and visual design have a measurable impact on learning. Even allowing students to select color has been shown to positively affect learning (Freedman, 1989; Longo, 2001).

ACCESSIBILITY

Guidelines for making software accessible to students with physical needs provide a second line of converging recommendations[1]. Of interest here are ways that software can be designed to make computer-based learning activities more accessible to students with various forms of physical challenges that are not debilitating, but require special attention. We omit "adaptive devices" such as special pointers for paraplegics, or Braille printers for the blind, because these require hardware and because these usually interact with software at the system level in a way that does not affect an application and does not require any special software functions.

The major categories of special needs are students with 1) mild learning disabilities, 2) attentional imbalances (deficits, hyperactivity), 3) language difficulties (English language learners, dyslexic students), and 4) physical challenges (partially sighted, hard-of-hearing). There is a limited number of ways that software can help.

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[1] A good set of guidelines can be found at http://ncam.wgbh.org/cdrom/guideline/

Vocalization. Obviously, sound provides an alternative input for those few students with vision difficulties, but it also helps the much larger special needs population in most other categories as well. English learners can often better understand information when spoken that when written. Students who are distractible, who have short attention spans, or who have learning disabilities can sometimes attend better to speech.

Enlargement. Making objects larger is again an obvious advantage for the partially sighted, but can help many students with special needs. Making something larger focuses attention on it, makes it easier to attend to, and reduces competing stimuli.

Stimulus level. Some students simply miss information unless it is bright, big, bold, fast, and high contrast. Others are easily over-stimulated and need just the opposite: quiet designs, harmonious and muted colors, slow action, and low contrast. Screens and computer-generated sounds should be designed with high, medium, and low stimulus levels.

Language Use. Poor reading skills are obviously a problem for dyslexics (10% of the male population) and recent immigrants, but it is important to remember that students right through college have difficulty reading. One-quarter of students entering community colleges need remediation in math and language because they perform far below par, so language help should be built into software. The text on screens should be as succinct and direct as possible. Software can provide vocabulary lookup (possibly providing explanations in several languages), audio or text-based pronunciation assistance, additional explanations, and vocalization on demand. The vocabulary and syntax used should be carefully controlled and the rate of text vocalization should be under student control.

Captions. Hearing impaired learners need captions whenever material is presented aurally. Captions can also help English learners acquire language skills.

Color blind. Screens need to be designed for the color blind, another 10% of the male population that is often overlooked. There is both red-green and blue-yellow blindness that need accommodation.

UNIVERSAL DESIGNS FOR LEARNING

UDL Overview

Universal design can be seen as a way of combining accessible requirements for special students with cognitive research that applies to all. Advocates of UDL tend to emphasize the needs of the majority of students who do not have special needs, but who profit from the kinds of software designs that do help special needs students. UDL is based on four tenets (CAST, 2000):

Students with disabilities fall along a continuum of learner differences rather than constituting a separate category.

Teacher adjustments for learner differences should occur for all students, not just those with disabilities.

Curriculum materials should be varied and diverse, including digital and online resources, rather than centering on a single textbook.

Instead of remediating students so that they can learn from a set curriculum, curriculum should be made flexible to accommodate learner differences.

The promise of UDL. Flexible design will result in materials and activities

> *that allow learning goals to be attainable by individuals with wide differences in their abilities… Universal Design for Learning is achieved by means of flexible curricular materials and activities that provide alternatives for students with differing abilities. These alternatives are built into the instructional design and operating systems of educational materials—they are not added on after-the-fact (Burgstahler, 2002).*

A UDL Framework

As a result of an extensive review of the literature by the National Center on Accessing the General Curriculum[2] CAST developed a framework for universal design (D. H. Rose & A. Meyer, 2002). They found that:

> *The key to helping all students achieve is identifying and removing barriers from our teaching methods and curriculum materials. Drawing from brain research and using new media, the UDL framework proposes that educators strive for three kinds of flexibility:*
>
> 1. *To represent information in multiple formats and media*
> 2. *To provide multiple pathways for students' action and expression*
> 3. *To provide multiple ways to engage students' interest and motivation*
>
> *The three UDL principles, implemented with new media, can help us improve how we set goals, individualize instruction, and assess student progress.* (Chapter 4 summary)

Implications of the Framework

UDL requires new assessments. Assessment strategies should match instruction, because it is neither accurate nor rational to rely on traditional written tests when UDL is used for instruction. Thus, a UDL mathematics curriculum needs to develop student assessments that have the same flexibility that is built into instruction. Computer technology makes it possible to embed assessment in learning activities and track student progress, so at least some of the assessment can use the same technology as instruction. Flexible, accessible assessment should be a central design feature of UDL (D. H. Rose & A. Meyer, 2002).

UDL can help all. UDL is exciting because it represents a convergence of thinking about the best uses of technology. It is inspired by the needs of special students, but it can improve the learning of all students. As the Center for Applied Special Technology (CAST) notes, "the future is in the margins." By helping students who are marginalized in traditional classrooms, schools and vendors will discover educational methods and materials that are flexible and powerful enough to help all students, regardless of their ability.

> *… a curriculum should include alternatives to make it accessible and appropriate for individuals with different backgrounds, learning styles, abilities, and disabilities in widely varied learning contexts. The "universal" in universal design does not imply one optimal solution for everyone. Rather, it reflects an awareness of the unique nature of each learner and the need to accommodate*

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[2] See http://www.cast.org/ncac/index.cfm?i=3117

> *differences, creating learning experiences that suit the learner and maximize his or her ability to progress*[3.]

UDL has been successfully applied to reading and the language arts. Experience in reading and language arts indicates that flexible, computer-based materials that help students who are marginalized can help students, regardless of their ability (Freed, Rothberg, & Wlodkowski, 2003). The nonprofit Center for Applied Special Technology (CAST) has developed two commercial reading products based on UDL that have been validated and are now reaching large numbers of schools[4].

An Example: *Thinking Reader*

The *Thinking Reader* product, a middle school reading comprehension package developed by CAST and Tom Snyder Productions, now a division of Scholastic, has the following characteristics that qualify it as UDL:

Display options. The student can control text size, color, and font. Not all menu items are controlled, however, so a partially sighted user may not be able to use the controls. The entire text or selected words can be vocalized. One of four voices can be selected, one of which is a recorded human voice.

Problem-solving options. The text is periodically stopped and students are asked to do one of seven reading comprehension tasks, such as summarizing or imagining. For each task, five ways of completing the task are provided from simply reading a good response (mentoring), to selecting the best of three responses, to completing a response, to free form. The teacher decides which of these five is appropriate for each student, usually by starting as low as necessary and slowing ramping up to the most difficult.

Personalization and interaction. Cartoon figures "converse" with the user, providing an element of personal identification. Students can choose to get input from these characters.

Student assessment. Student progress is summarized and made available in a nice format. Summary information is in a table but teachers can drill down to see more detail and even student work.

The *Thinking Reader* is a shell into which different literature can be inserted. Scholastic owns popular, high-quality texts and has put several into this product to increase its perceived value.

This relatively simple implementation of UDL is a compromise between what is possible and feasible. It was expensive to develop and is not a runaway best seller, unlike their remedial reading product.

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[3] See http://cast.org/udl/index.cfm?i=7

[4] See http://www.teachtsp.com/products/product.asp?SKU=THITHI&Subject=LanguageArts and http://www.teachtsp.com/products/product.asp?SKU=WIGWIG.

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