Enhancing Materials Research Through Innovative 3D Environments and Interactive Manuals for Data Visualization and Analysis

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ABSTRACT

Spatial intelligence plays an important role in the success of nanoscience students specific to their visual ability to perceive structures in three dimensions. The NSF-funded IDEAS project makes use of a unique interactive 3D visualization system, based on immersive environment technology, for research and learning in Materials Science and Engineering (MSE) at UC Merced. In order to determine the effectiveness of the immersive system on nanoscience learning, a pilot project was conducted with undergraduate students, which showed the success of immersive systems in the science learning process. Overall, the immersive environment provided complete control in the construction and analysis of carbon-based nanostructure models. Results also showed the 3D visualization system benefited students with low spatial abilities. To facilitate a better understanding of the structure and properties of nanostructures, the IDEAS project has recently been expanded to allow accelerated simulations for materials research. It is important to integrate these new applications into undergraduate level courses in order to strengthen materials science education, recruit and retain future students, and to adapt modern technologies for future materials science educators. The expansion of the IDEAS project relies on the flexibility of this system to serve as a research tool as well as an innovative resource for science education. To adapt the 3D visualization and computing system and help engage students early in engineering research, our research group gathered practical technical documentation geared towards education of science users, based on both Cognitive Science and MSE Education (MSE-Ed) research. The work presented here involves developing educational resources through the design of audio-visual manuals for effective nanoscience learning. The manuals are being created using commercial software to produce interactive electronic books (e-books). During the planning of the audio-visual manuals, we discovered that it is imperative to provide adequate educational tools as well as efficient guiding principles for the large number of visual, inductive, and active learners in general engineering education. This interdisciplinary project combines fundamental concepts from materials science and cognitive science, particularly project-based learning and active processing, while considering the concepts of overloading, and the unreliability of natural language, among other topics. This investigation will serve society by enhancing materials science research and education, as well as influencing engineering, chemistry, computer science and cognitive science fields, among others.

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INTRODUCTION

Many educational methods and tools are readily available today for materials science and engineering learning and education [1-5], especially given the continuing advances in technology [1-4, 6-8]. Some of the recent advancements involve modern hardware and software, visual methods and sophisticated graphics [1, 5-8]. Figure 1 illustrates the use of 3D visualization and
immersive technology for research by a student at UC Merced. Furthermore, many modern resources are readily available through the Internet, while others can be customized to meet the students’ needs using visual graphics software such as Matlab and Labview. Other options are also available including online tools for effective digital reading (see Table A in Appendix).

Figure 1. Undergraduate engineering student creating and interacting with a carbon nanotube model in a 3D visualization and computing system in the Davila laboratory at UC Merced.

In 1999, a report on the state of MSE Education (MSE-Ed) released detailed information on the style and historical progression of materials science educational development in the US and Europe. This report [9] revealed key findings including the following: (1) there has been excessive variation in materials science higher education with regard to instructional structure; (2) computer simulations have had a significant impact on MSE; and (3) MSE requires adaptive tools to promote effective learning. Perhaps the most important conclusion of the report was the need for technology in MSE to bridge the gap between theory and practice in education. In the area of cognitive science, theories of learning are being applied to enhance the learning experience (e.g. of college students), and to pinpoint the challenges of higher education [10].

The objective of this project is to develop multi-media manuals that can be adapted to 3D visualization and computing systems in order to provide researchers with effective interactive science learning tools. These innovative means of learning also have the potential to facilitate the training of researchers/educators to ensure efficient interaction with these modern systems.

In this study, extensive research was conducted in MSE-Ed and Cognitive Science. One benefit of the work is that it shows that an educational tool alone does not guarantee successful learning in students [11-12]. It is also necessary to provide adequate direction and context on how to use the proposed learning tool. In the development of audio-visual manuals, important considerations included student learning styles and their impact on education, previous and current learning methods and tools in MSE, the importance of visualization in learning, and prior experiments related to the implementation of new teaching tools in engineering education.

The general approach for this work involved: (1) creating a comprehensive interdisciplinary literature review (on learning styles and education, imagery, and teaching technology and its impact in engineering education), (2) identifying the main traits for an effective multi-media (audio-visual) manual for science learning, (3) designing a prototype interactive e-book, and (4) testing the manual for the 3D visualization system through an e-book reader.
PROCEDURE

The interdisciplinary literature review leading to the design of a multi-media manual for science learning is summarized next (step 1 in general approach above). The identification of the main traits of an effective audio-visual manual, design of a prototype, and testing of the manual will be described afterwards (Results section).

Learning Styles, Engineering Education, and Technology

We took into account the many learning styles presented in the “Learning Styles Inventory” which is widely known in education [13] due to its successful categorization of a person’s optimal learning style. Felder’s matrix [14] along with Kolb’s learning styles inventory [13] describe learning as a process consisting of four phases: concrete experience (feeling), reflective observation (reflection), abstract conceptualization (thinking), and active experimentation (doing). Also, students are often categorized through the Felder and Silverman model [14] as active or reflective, sensing or intuitive, visual or verbal, and sequential or global which can guide their learning process. A four-year study [15] investigated whether knowledge of personal learning style would be beneficial in a university setting. Results indicated it is the application of learning styles in organizing teaching (and learning) materials that is important. The above studies infer the need of adaptable educational materials including audio-visual manuals, which will allow for individual learning styles.

Research has shown that in Engineering education there is a great discrepancy between the method of instruction and the preferred method of learning. Felder [14] indicated engineering information should be concrete and abstract, thus induction, which is reasoning that proceeds from details to generalities, was recommended. However the traditional college teaching method is deduction, which begins with “fundamentals” and proceeds to applications (or generalities to details). Most engineering students are hence visual, sensing, and active; most engineering education is auditory, abstract, deductive, and sequential. This can lead to poor student performance, professorial frustration, and a possible loss of many potentially excellent engineers.

Many studies have investigated the role of technology on learning [1, 5-8]. For instance, Keehner et al. [16] discovered that complete control of computer visualization does not enhance task performance by students, rather it is receiving the most task-relevant information that has a significant effect on their performance. In other words, as long as there is extensive relevant information and training for a task, active or passive learning is not a significant factor in students’ learning. Furthermore, it is widely believed that hands-on learning is effective because of its tactile influence, but it has been shown that it is the information which is presented to participants which contributes to the comprehension and success of a task. As technology is quickly advancing it offers many different devices, which allow for tactile-like activities, including the use of versatile input devices and tracking systems [7-8].

Empirical multimedia research indicates that students learn better when presented with simultaneous and equally consecutive words and images [10, 17], as summarized in Table B (see Appendix). This is important to enabling effective processing of information by learners, which is an active cognitive process for constructing logical mental representations, as illustrated in
Other investigators [18-19] have also identified a limited capacity for holding and manipulating knowledge which can overload the learner. The above studies suggest the value of multimedia resources to enhance the learning process.

**Figure 2.** Illustration of a model of mental processing [10].

**Role of Visualization and Computation in Materials Science**

The importance of visualization in education has been described by Ramadas [20] through his research summarizing knowledge of visual and spatial thinking from cognitive science, developmental psychology, science literacy and science studies. Results showed imagery is not only created through sight but also via transformational reasoning. Mathewson [21] asserted that since science learning relies heavily on incremental learning, and incremental learning in turn relies on visual-spatial thinking, therefore (K-12) curriculum must account for this when implementing learning activities. The value and impact of visual representations specific to spatial ability were reported in a study [22] in which students used a hypermedia software package designed to teach about the structure of cell elements present in plants and animals. The study concluded that while spatial ability differs among learners, 3D interactive models mostly benefit those with high spatial ability. Students with low spatial ability seemed to be overloaded as continuous usage of the system was observed.

Brown et al. studied research on computer simulations as an educational tool to augment or even replace traditional field experience [23]. But as results showed, simulations cannot currently replace field experience. On the other hand, it was explained that because of the natural human attraction to play, simulations may have a positive implication in education. Therefore, as advancements in technology improve computer simulations, related instructional methods must continue to be studied to evaluate their impact on learning. More recently, visual aids were implemented in engineering education at a large state university, as the students there preferred the visual learning method [5]. Cadena reported that this method seemed to be complemented by audio, kinesthetic, and tactile means [5]. Furthermore, Thornton et al. conducted a comprehensive assessment of the state of computational materials science and engineering (CMSE) education in the US, showing general support for integrating computational content into MSE [Thornton 09]. The authors reported that some computational faculty and researchers indicated that CMSE has been used as a “virtual laboratory” to deliver MSE concepts often difficult to demonstrate in a traditional laboratory. In addition, surveys revealed the need to further integrate computational methods into materials science curriculum [1].
Effective Manual Guidelines

Connecting past educational materials with current manual writing guidelines has proven to be the key to improving the development and acceptance of manuals for use with advanced technology. Educational theories were also investigated, as well as manual creating guidelines like Horton’s “Designing and Writing Online Documentation” [24]. It is through minimalism that readers were found to be engaged for the amount of time needed in order to complete a task. Minimalism is the task-oriented approach to instruction and documentation that emphasizes the importance of realistic activities and experiences for effective learning and information seeking. User control of activities and dialog within a manual, especially that displayed through text as language, allows for this experience and is an intricate part of creating a useful manual. Shneiderman [25] reviewed many manual guidelines based on practice and empirical studies. These guidelines included the advantages and disadvantages of reading from different types of displays while avoiding common pitfalls.

Many engineering students are visual learners, which contradicts teaching methods that are focused on audio learning [14]. Many teaching aids are based on text reading with minimal visual aid or hands-on interaction. Further data depicts the necessity and ability to improve education and communication through imagery. Finally, the enhanced learning through visual aids does not simply involve the provision of visual representations of complex structures, otherwise not available or too difficult to imagine, or the relation of past knowledge through imagery. It is the ability to derive more task relevant information from visualization in addition to the provision of visual representations that induces deeper learning.

RESULTS

Based on above literature review, the main traits for an effective audio-visual manual were identified for science learning. Table C (see Appendix) summarizes the key features to consider for the design of a prototype of an audio-visual manual. It was established that the computerized manual needed to have a balance between static images and animations. Also, it is important to ensure that the user not be overloaded with continuous animations, have optional text, continuous audio and ability to pause, and have complete control of manual speed. Next, an interactive manual in the form of an e-book was designed and created based on educational theories, shaping content using various principles [26], and extensive relevant guidelines [27]. The integration of the (e-book) manual to the 3D visualization system and tests to obtain an optimum balance of visual and audio data (see Table D in Appendix) are underway. Finally, the effectiveness of the audio-visual manual in science learning will be tested in a pilot project.

E-book Development

The instructional e-book for the 3D visualization and computation system was created following the guiding principles in Table C (see Appendix) using commercial software package (iWorks Pages). The resulting audio-visual manual was designed to be accessible via any e-book reader, and to be simple in format to allow editing and use with future adaptation to the 3D visualization system. The main steps in this development and an example e-book are shown in Figures 3-4.
Figure 3. Step-by-step developmental process to create an e-book.

Figure 4. Interactive e-book for MSE research and learning. Key features include (a) hyperlinks to resources, text, glossary, and (b) video, audio, annotation and other menu options.

DISCUSSION

The “Instructional Theory into Practice” model [26] is often used to outline the five key curriculum design principles that underlie all direct instruction programs and are fundamental to most instructional materials. These principles state the need to: (a) identify “big ideas” (or ideas that appear frequently) to organize content, (b) teach explicit general strategies, (c) scaffold instructions, (d) integrate skills and concepts, and (e) provide adequate means of review. Of these principles, we applied three which are most relevant to creation of the audio-visual manual. These are: organizing content based on big ideas which appear frequently, teaching explicitly, and using scaffolded instruction which includes a temporary framework for support, and access to meaning. This will strengthen the clarity and success of the audio-visual manual content as well as the consistent presentation of information.

Perhaps the most important article by Shneiderman [25] describes the guidelines for the creation of a manual originally established by Carroll [27]. These guidelines are based on practice and empirical studies, and include conciseness, wording, and possible determinants. This extensive list of established guidelines helped to serve as a template for a successful manual. In a case study of science and engineering education [15], the authors reported the lack of a need for teaching students about their learning styles. This finding proves to be most useful when determining what background information will be given to equip the user with the most task relevant information and to ensure their success in interacting with the manual. Because in our experience students seem to benefit from learning about learning styles, it will be our focus to apply the learning styles in organizing our materials and content.

The guidelines referred to previously will allow us to provide users with the best possible tools to optimize learning in material science. The audio-visual manual designed will balance past technical document guidelines as well as educational findings and theories. The manual will be
computerized with a balance between static images and animations, optional text, and will take advantage of multiple windows, text highlighting, and sound. The two most critical guidelines which will be followed during the future creation of manuals will be the complete control of manual options by the user, and the careful balancing of images and text to not overload the user with continuous animations. The large number of visual, inductive and active learners in engineering has been taken into consideration for the design and implementation of the e-books.

CONCLUSIONS

The above interdisciplinary review served as a basis for the creation of audio-visual manuals which will be adapted to 3D visualization and computing systems for the application of different learning styles. The design of audio-visual manuals was organized around the effective presentation of words and pictures. It has been shown in our previous project that students with lower spatial ability benefit more from the use of the 3D visualization system. This contrasts studies by Huk [22] as different visualization methods were used. Further research needs to account for such variation. It has been acknowledged that there is a need for new educational tools in material science education because of a discrepancy in teaching methods and learning styles in the sciences. This work will help in developing innovative audio-visual manuals to provide users with proper training for a successful interaction with visualization systems.

In general, our research has led to a set of fundamental concepts to consider when designing audio-visual manuals for science learning. Future tests to compare students’ receptiveness to a continuous document (e.g. textbook or printed manual) compared to a completely user-controlled document (e.g. e-book) are necessary to more completely evaluate these approaches. We also found that it would be important to determine the appropriate number of audio and visual elements in the e-books to obtain the correct balance for an optimum learning experience. The resultant e-books created in this project will serve as a foundation for additional specific e-books for materials science research and learning, to be used in a summer pilot project which will measure the students’ receptiveness to such user-controlled interactive documents. A previous pilot study showed our 3D visualization system benefited students with low spatial abilities. We plan to evaluate the impact and best practices of the audio-visual manuals designed here, as they are likely to offer optimum learning experiences.

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DISCLAIMER

At the date this paper was written, URLs or links referenced herein were deemed to be useful supplementary material to this paper. Neither the author nor the Materials Research Society warrants or assumes liability for the content or availability of URLs referenced in this paper.
REFERENCES

APPENDIX

Table A. Available online tools for effective digital reading.

<table>
<thead>
<tr>
<th>TOOL</th>
<th>DESCRIPTION</th>
<th>WEBSITE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Instapaper</td>
<td>Facilitates the reading of long text content. Allows user to save and access content on desktops, e-book readers, iPads, etc.</td>
<td><a href="http://www.instapaper.com/">http://www.instapaper.com/</a></td>
</tr>
<tr>
<td>Diigo</td>
<td>A web-based application that allows user to collect, highlight, and retrieve web content.</td>
<td><a href="http://www.diigo.com/">http://www.diigo.com/</a></td>
</tr>
</tbody>
</table>

Table B. Learning principles based on audio and visual stimulation [17].

<table>
<thead>
<tr>
<th>Multimedia Principle: Students learn better from words and pictures than from words alone.</th>
<th>Practical Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>On screen animation, slide shows, and narratives should involve both written or oral text and still or moving pictures. Simple blocks of text or auditory only links are less effective than when this text or narration is coupled with visual images. (Sample example).</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Spatial Contiguity Principle: Students learn better when corresponding words and pictures are presented near rather than far from each other on the page or screen.</th>
<th>Practical Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>When presenting coupled text and images, the text should be close to or embedded within the images. Placing text under an image (i.e., a caption) is sufficient, but placing the text within the image is more effective. (Sample example)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Temporal Contiguity Principle: Students learn better when corresponding words and pictures are presented simultaneously rather than successively.</th>
<th>Practical Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>When presenting coupled text and images, the text and images should be presented simultaneously. When animation and narration are both used, the animation and narration should coincide meaningfully. (Sample example)</td>
<td></td>
</tr>
</tbody>
</table>
### Table C. Key characteristics of effective audio-visual manuals.

<table>
<thead>
<tr>
<th>FEATURE</th>
<th>INFORMATION</th>
<th>PURPOSE</th>
<th>NOTES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Audio</td>
<td>Optional spoken step by step directions that follow the written manual.</td>
<td>Allows for auditory stimulation. Optional sound allows for halting before overload.</td>
<td>Minimal audio is intended.</td>
</tr>
<tr>
<td>Closed Captioning</td>
<td>If video directions are chosen then closed captioning will be provided.</td>
<td>For use with videos in help section.</td>
<td>Only available as an option if selected at the beginning.</td>
</tr>
<tr>
<td>Visual</td>
<td>Static images presented and optional animations presented when user presses the help menu.</td>
<td>Necessary throughout the manual.</td>
<td>Static images located on a second screen.</td>
</tr>
<tr>
<td>Help Menu</td>
<td>Help menus distributed throughout the manual for further explanation on hardware, functionality, etc.</td>
<td>Help buttons located throughout the pages with video tutorials of actual usage.</td>
<td>Optional only if selected.</td>
</tr>
<tr>
<td>Brief</td>
<td>Simple to keep the user focused.</td>
<td>To sustain user attention.</td>
<td></td>
</tr>
<tr>
<td>Portable</td>
<td>On an e-reader to allow for mobility and fewer distractions.</td>
<td>To alleviate overloading from switching between desktop and 3D system.</td>
<td>Consider iPad, Entourage, etc.</td>
</tr>
<tr>
<td>Web Accessible</td>
<td>Links throughout the manual will give user access to the web for definition of terms.</td>
<td>Monitor manual content but limit access.</td>
<td>Only accessible. Avoid web-based manual. Nothing should have to be accessed on the web.</td>
</tr>
<tr>
<td>Expanding Links</td>
<td>Links that give the user access to sub-links related to terms in the table of contents.</td>
<td>Visual track of user’s past links.</td>
<td>Not drop down menu, only for table of contents.</td>
</tr>
<tr>
<td>Fill-in Search Bar</td>
<td>Allows the user to quickly search titles.</td>
<td>Using the drop down menu allows for further searching within a sub-section for key terms.</td>
<td>For search menu, bookmarks, history links.</td>
</tr>
<tr>
<td>Contrasting Window</td>
<td>Allows for black background and colored text for the visually impaired.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>History Window</td>
<td>Easy navigation through past actions.</td>
<td>Bookmarking and other comments as done in physical books.</td>
<td></td>
</tr>
<tr>
<td>Magnifier</td>
<td>Bigger fonts for the visually impaired.</td>
<td>Giving the user constant control of font size.</td>
<td></td>
</tr>
</tbody>
</table>

### Table D. Audio-visual manual matrix showing optimum balance of features.

<table>
<thead>
<tr>
<th>LANGUAGE</th>
<th>VISUALS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speech (Continuous vs. Pauses)</td>
<td>Static Images</td>
</tr>
<tr>
<td>Text</td>
<td>Moving Images (Animations)</td>
</tr>
</tbody>
</table>