Changes in Students’ Science Ability Produced by Multimedia Learning Environments: Application of the Linear Logistic Model for Change

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The purpose of this study was to measure changes in students’ science proficiency produced by a multimedia learning environment, Astronomy Village: Investigating the Solar System, developed at Wheeling Jesuit University’s Center for Educational Technologies with funding from the National Science Foundation. The inquiry-based design of Astronomy Village supports middle school students in learning fundamental concepts in life, earth, and physical science. Astronomy Village was compared to an alternative treatment that simulated elements of traditional science instruction using web site access to background materials and content in Astronomy Village. The results indicate sizable treatment effects for two groups of Astronomy Village students, as well as for the alternative treatment group. Differences in the treatment effect sizes among the three treatment groups reveal the relative merits of different approaches to using technology. The Linear Logistic Model for Change applied in this study is beneficial for comparing alternative uses of technology, since it separates effects due to treatments from natural trend effects and eliminates drawbacks of traditional statistical designs for pretest-posttest changes.

During the 1990’s, K-12 schools in the United States steadily increased the amount they spent on technology. In 2001, school spending on hardware and software is expected to exceed $10 billion (Kamp, Blohm, Tyre, Williams, Schneiderman, 2000). Schools are increasingly being held accountable for their decisions and technology purchasing is no exception (Bush, 2001; Kronholz, 1999). However, linking technology access to broad-scale accountability instruments, such as the National Assessment of Educational Progress (NAEP), is extremely difficult. This difficulty is highlighted by recent reports about the impact of technology use on NAEP math and reading scores (Wenglinsky, 1998; Johnson, 2000). Technology access alone is not a significant predictor of positive performance on NAEP tests. Instead, researchers need to consider the manner in which the technology is used. In the case of NAEP math scores, use of drill and practice software was negatively correlated with performance, whereas use of problem-solving software was positively correlated with performance (Wenglinsky, 1998). In order to maximize their investment in technology, schools should move beyond questions of whether technology is effective. Instead, they should be investigating (a) how to use technology effectively in the classroom and (b) how to measure changes in students’ proficiency in science as a result of using technology.

Traditionally, changes in variables such as achievement and attitude have been measured by differences between pretest and posttest scores. Recent studies of changes and effects in the context of science and mathematics education do not make an exception (see, e.g., Chang & Mao, 1999; James, Lamb, Householder, & Bailey, 2000; Parker & Gerber, 2000). It should be noted, however, that this approach has serious drawbacks. First, difference scores are less reliable than the scores entering the difference (e.g., Allen & Yen, 1979, p. 208). Second, raw scores are test dependent (i.e., depend on the difficulty of the test). Third, raw scores do not adequately represent response patterns, since different response patterns on test items may lead to the same raw score. Fourth, pretest to posttest raw score differences do not separate changes due to experimental treatments from changes due to natural trends, such as maturation and experience. Finally, raw score differences do not provide information about magnitudes of change on a ratio scale—in other words, it is not known how many times a given change effect is larger than
another change effect. Item response theory models such as the Linear Logistic Models for Change (LLMC) eliminate problems with the classical pretest-posttest score differences and provide additional information for valid interpretations of the results (Fischer, 1995). More information about the LLMC is provided in the next section.

The purpose of this study was to measure changes in students’ science proficiency, using the LLMC, in the summative evaluation of Astronomy Village: Investigating the Solar System, developed at Wheeling Jesuit University’s Center for Educational Technologies (CET) with major funding from the National Science Foundation and additional support from NASA (see McGee & Howard, 1999). The development effort for Astronomy Village spanned 4 years (1997-2001), including 2 years of formative evaluation. The current study focuses on the summative evaluation, which occurred in fall 1999, using a near final version of Astronomy Village. The final version of Astronomy Village was released in February 2001.

Method

Astronomy Village

Astronomy Village is designed to teach middle school students fundamental concepts in life, earth, and physical science by having them investigate cutting-edge questions related to the solar system (McGee & Howard, 1999). Students are transported to a virtual village in Hawaii where they investigate one of two Core Research Projects: Mission to Pluto or Search for Life. The program is designed such that a virtual mentor guides students in completing multiple investigation cycles that mirror the phases of scientific inquiry. For example, in the Search for Life Core Research Project, students are introduced to the problem of searching for life. They must first understand what the core requirements for life are before they can begin to search for those core requirements on other planets and moons. During the exploration phase of the investigation, students brainstorm a list of requirements for life. Then, students review the Life on Earth dataset in Astronomy Village to investigate life forms in a variety of biomes on Earth. Students pay particular attention to life forms in extreme environments. In the background research phase, students read library articles, listen to lectures, and conduct hands-on activities to help them understand key background concepts related to life forms in extreme environments on Earth. During the data collection and analysis phases, students return to the Life on Earth dataset to collect environmental data from each

of the biomes in the dataset. The students plot the data to determine the upper and lower limits of various environmental conditions for supporting life. In the presentation phase, students complete the investigation by hosting a press conference in front of a virtual press corps that asks students questions about the investigation they have just completed. This project lasts about 1 week.

Students then follow the same sequence of phases as they did in the Core Research Project when they undertake a Focused Investigation on a narrow topic related to the Core Research Project. For example, students may investigate whether icy volcanoes could exist on Pluto by examining the surfaces of other icy bodies in the Solar System. Or students may examine temperature/pressure relationships on a variety of planetary bodies to determine where the conditions are right to support liquid water.

Evaluation Design

For the summative evaluation of Astronomy Village, CET researchers were most interested in how technology could be effectively used to teach interdisciplinary content ideas related to the surface of Pluto and the search for life. Therefore, they were not interested in comparisons between technology use and no technology use. Instead, the treatment design compared alternative uses of technology for teaching the same interdisciplinary content. Through a content analysis of the software, CET researchers determined that the unique strength of the software lay in the use of image analysis to answer important research questions. Therefore, the comparison focused on access to image analysis activities versus no access to image analysis activities. The comparison students studied the same content using the same technology as Astronomy Village students used, but were denied access to the image analysis capabilities. These comparison students were deemed the alternative treatment group. As required by the LLMC design used in this study, a “no treatment” control group was also used for the pretest and posttest measurements.

The alternative treatment group was provided with the collection of background materials in Astronomy Village that supports each investigation: lectures, library articles, and hands-on activities. These materials were presented through a web site specifically designed for the alternative treatment group. Given a focus on content-related activities only, the alternative treatment group was able to cover all of the topics in Astronomy Village over a 4-week period. This is reminiscent of traditional approaches to science education that focus
on covering a wide array of content at a superficial level. In contrast, the students in the Astronomy Village treatment group participated over an equivalent 4-week period but covered only the topics related to one of the two Core Research Projects. Astronomy Village students engaged in both the content-related activities, as well as the inquiry-oriented image analysis activities. This evaluation design held technology as a constant and fostered a comparison between traditional breadth approaches and the depth approaches recommended the National Science Education Standards (National Research Council, 1996). As will be seen in the following section, such a comparison is possible in this study because the assessment domain of the pretest-posttest instrument is large enough to encompass measurements of learning outcomes for all treatment groups. The assessment approach in this study allows for evaluation of how much students are capable of transferring what they have learned into areas they have not directly studied.

**Instruments**

Large-scale measures such as NAEP and Third International Mathematics and Science Study are designed to represent the entire domain of school science and tend to focus on content-related performance expectations. Very few large-scale items focus on the kinds of inquiry-related performance expectations promoted by Astronomy Village. Therefore, CET researchers developed an assessment instrument that is attuned to the topics and performance expectations in Astronomy Village.

Three principles guided the design of the assessment instrument used in this study. First, the assessment instrument should reflect important thinking and problem solving skills from the discipline of planetary science (Hickey, Wolfe, & Kindfield, 1999; Sheppard, 2000). In both the Astronomy Village group and the alternative treatment group, students investigated authentic questions, such as whether liquid water exists in the solar system, that require important thinking and problem solving skills from the discipline of planetary science. Therefore, this principle was achieved by designing assessment tasks that reflected the thinking and problem solving targeted in Astronomy Village.

The second guiding principle was measuring the extent to which students transferred their thinking and problem solving skills into new contexts (Bransford, Brown, & Cocking, 1999). This principle reflects the philosophy that a critical aspect of education is whether learning transfers (Sheppard, 2000). When there is no specific transfer situation, the assessment becomes the transfer situation (Hickey et al., 1999). Astronomy Village supported transfer by having students investigate critical processes and features on a variety of planets and moons. For the assessment instrument, students had to transfer their understanding to hypothetical planets and moons.

The third guiding principle was ease of administration and scoring for the target population. In prior research at the high school level, CET researchers have had success measuring complex problem solving and argumentation abilities using an extended response format (Hong, 1998; Hong, McGee & Howard, 2001). However, at the middle school level, there was concern that the extended response format would be a better reflection of students’ writing abilities than their problem solving abilities. In addition, the extended response format was too labor intensive to score within the budget limitations of the project. CET researchers, therefore, chose to use a machine-readable multiple-choice format. Taking into account the three guiding principles collectively, CET researchers felt confident in developing an assessment instrument that would measure important learning outcomes in a cost-effective manner.

CET researchers identified the key complex content ideas presented in each of the nine investigations within Astronomy Village. Item writers were contracted to develop the assessment items related to the underlying concepts within the investigations. In addition to measuring complex content understanding, students were expected to learn basic problem-solving skills related to drawing conclusions from data and inferring planetary processes from analyzing images of surface features. Two test scales, content understanding (22 items) and problem solving (40 items), were developed, with items related to learning outcomes for both the Search for Life and Mission to Pluto projects described in the previous section. In a typical problem-solving item, a student is shown a satellite image and asked to identify what major geologic structure is represented in an image and what underlying process formed the geologic structure (see appendix for examples).

The content understanding and problem solving scales were administered to all students as a pretest and posttest. Because none of the treatment groups studied the entire assessment domain, this study involved an investigation into which approach supports the greatest amount of both learning what was studied and transfer to what was not studied. The Astronomy Village students studied the content and problem solving from one Core Research Project (Search for Life or Mission
to Pluto) but not the other. The alternative group students studied the content from both Core Research Projects, but they did not engage in any problem solving activities.

Participants

A total of 837 students from schools around the United States participated in the two Astronomy Village groups (590 students), alternative treatment group (117 students), and control group (130 students) for whom data was collected. Thirty-eight percent were female, 40% were male, and 22% did not indicate their gender. Forty-eight percent were Caucasian, 9% were Asian/Pacific Islander, 6% were Hispanic, 3% were African American, 2% were other, and 32% did not indicate their ethnicity. The grade level breakdown was 12% fifth grade, 16% sixth grade, 37% seventh grade, and 35% eighth grade. The gender, ethnic, and grade levels were proportionally balanced for the Astronomy Village, alternative treatment, and control groups.

Teachers were recruited to participate in the evaluation of Astronomy Village through an application process. In spring 1998, the Center for Educational Technologies issued a call for applications. Out of over 50 applicants, 15 teachers were selected to participate. This selection was based on identifying typical teachers who (a) had sufficient access to at least the minimum hardware and software and (b) adequately represented the ethnic and geographic distribution of students in the United States. These teachers participated in formative testing of the Search for Life modules. Twelve of the teachers returned in summer 1999 for participation in the summative evaluation of the program, which is reported here. These teachers were trained during a summer workshop on how to use the software and how to administer the assessment instruments. Seven of the teachers decided to have their students investigate Mission to Pluto. The other five decided to have their students investigate Search for Life. Both groups were instructed to have their students spend approximately 4 weeks completing as many of the focused investigations under the Core Research Project as possible.

In spring 1999, a second call for applications was issued for teachers wishing to participate as an alternative treatment group. Five teachers applied. All five teachers were accepted to participate, since they all met the minimum hardware and software requirements and were representative of the ethnic distribution of the Astronomy Village group. These teachers were trained during a separate summer workshop in 1999 on how to use the web site to teach the core concepts, as well as implement data collection procedures. Both the Astronomy Village teachers and the alternative group teachers received the same amount of training in summer 1999. The alternative group teachers were asked to cover as much of both topics as they could in the same 4-week timeframe given to the Astronomy Village group. Unlike, the Astronomy Village teachers, the alternative group teachers focused only on the content related activities.

In addition to the Astronomy Village and the alternative treatment groups, participating teachers were asked to recruit another teacher at their school for the no treatment control group.

The evaluation took place in fall 1999. Given the geographic distribution of teachers, it was not feasible for members of the evaluation team to conduct classroom observations to verify the treatment conditions. Instead, CET researchers convened a meeting in March 2000 of all of the participating Astronomy Village and alternative group teachers. At that meeting the teachers provided a description of how they implemented the program. The teachers were also provided with the results of the assessments at an aggregate level and were asked to discuss how their implementation facilitated or hindered student learning. The results of these discussions indicated that the teachers indeed implemented their respective treatments in accord with the instructions they were given.

The Linear Logistic Model for Change (LLMC)

As noted earlier, the LLMC eliminates drawbacks of the traditional pretest-posttest design, provides information about the magnitude of the changes on a ratio scale, and separates changes due to treatment from changes due to natural trends across time points of measurements (e.g., pretest and posttest). The strict theoretical framework of the LLMC is not presented here because of its relative complexity and prerequisites of psychometric background for the reader (e.g., Fischer, 1995; Fischer & Ponocy-Selig, 1998). This section provides basic concepts and interpretations that are necessary for adequate understanding of LLMC results used in this study.

In the item response theory context, the term ability connotes a latent trait underlying the student's performance on a test (e.g., Hambleton, Swaminathan, & Rogers, 1991). The ability score of a student relates to the probability for this student to answer correctly any test item. The units of the ability scale, called logits, typically range from -4 to +4. They represent natural logarithms of odds for success on the test items. If a student succeeds on 75% of the test items and fails on 25%, the odds ratio for the test is 3/1 = 3. Thus, the
ability score of this student is the natural logarithm of 3, which is 1.10 (i.e., about 1 unit above 0 on the logit scale). It should be noted that the difficulties of the test items are measured on the same (logit) scale. If the ability \( \theta_j \) of student \( j \) equals the difficulty \( \beta_i \) of Item \( i \), the probability \( P_{ij} \) for Student \( j \) to answer correctly Item \( i \) is .5 (i.e., 50\% chances of correct answers). In the other two cases: (a) \( P_{ij} > .5 \), for \( \theta_j > \beta_i \), and (b) \( P_{ij} < .5 \), for \( \theta_j < \beta_i \).

With the LLMC design, the pretest to posttest change in the difficulty of a given item, \( \Delta \beta_i \), is interpreted as an ability change (effect) because item difficulty and student’s ability are measured on the same (logit) scale. The \( \Delta \beta_i \) effect has two components: (a) treatment effect, \( \eta \), due to the treatment, and (b) trend effect, \( \tau \), due to “natural trends,” such as biological maturation or cognitive development over the period of time between pretest and posttest measurements. For the treatment groups, \( \Delta \beta_i = \eta + \tau \), whereas for the control group \( \Delta \beta_i = \tau \). The ratio of two (\( \eta \) or \( \tau \)) effects indicates how many times one of the effects is greater (or smaller) than the other effect. The interpretation of the magnitude of an effect is facilitated by calculating the exponent (\( e \approx 2.718 \) of the effect. For example, with \( \eta = 0.5 \) (in logits) for a treatment group, \( e^{0.5} = 1.65 \) indicates that the odds for success on the test for this group are 1.65 times higher than the odds for the control group (reminding that \( \eta = 0 \) for the control group). The LLMC used in this study works with dichotomously scored items (1 = correct, 0 = incorrect) and assumes that the data fit the Rasch model (Rasch, 1960; see also Fischer & Ponenocy-Selig, 1998).

In this study, pretest to posttest treatment effects and trend effects are provided for the Astronomy Village group and the alternative treatment group by comparing each of them to a control group on the content understanding and problem solving scales. The LLMC calculations were performed using the computer program LPCM-WIN 1.0 (Fisher & Ponenocy-Selig, 1998).

**Results and Interpretation**

The three treatment groups, Search for Life, Mission to Pluto, and alternative groups, were compared against the same control group with a LLMC design for the calculation of treatment effects, \( \eta \), and trend effects, \( \tau \), on each of the two scales: content understanding (22 items) and problem solving (40 items). The Cronbach’s reliability coefficient was adequate for the purposes of these comparisons, with values of .80 (content understanding scale) and .97 (problem solving scale). The results in Table 1 show that there was no statistically significant trend effect, \( \tau \), for any of the treatment groups. This is not a surprise given the relatively short period of 4 weeks between the pretest and posttest. Indeed, one can hardly expect changes in natural maturation or cognitive development over a short period of time. By reverse, there were statistically significant treatment effects (\( \eta \)-effects in Table 1) for the three treatment groups on each scale, content understanding and problem solving. This indicates that all three treatment groups achieved significant learning gains on both content and problem solving.

On the content understanding scale, all treatment groups achieved significant learning gains, with the highest pretest to posttest change of students’ ability on the test (in logits) for the Search for Life group (0.660) followed by the alternative group (0.645), and the Mission to Pluto group (0.385). The ratio of treatment effects for the Search for Life and Mission to Pluto groups (0.660/0.385 = 1.71) indicates that the learning gain for the former was 1.71 times greater than for the latter group. In other words, the odds for success on content understanding are 71\% in favor of the Search for Life group compared to the Mission to Pluto group. Similarly, the odds for success on content understanding were 68\% in favor of the alternative group compared to the Mission to Pluto group, as indicated by the ratio of treatment effects for these two groups (0.645/0.385 = 1.68).

<table>
<thead>
<tr>
<th>Group</th>
<th>Content ( \eta )</th>
<th>Problem Solving ( \eta )</th>
<th>Content ( \tau )</th>
<th>Problem Solving ( \tau )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Search for Life</td>
<td>0.660** (0.070)</td>
<td>0.598** (0.053)</td>
<td>0.105** (0.059)</td>
<td>0.126 (0.043)</td>
</tr>
<tr>
<td>Mission to Pluto</td>
<td>0.385** (0.068)</td>
<td>0.415** (0.050)</td>
<td>0.105** (0.059)</td>
<td>0.126 (0.043)</td>
</tr>
<tr>
<td>Alternative</td>
<td>0.645** (0.079)</td>
<td>0.464** (0.063)</td>
<td>0.105** (0.059)</td>
<td>0.126 (0.043)</td>
</tr>
</tbody>
</table>

*Note. \( \eta \) = treatment effect; \( \tau \) = trend effect. All effects (with standard errors in parentheses) are on the same scale (in logits). The ratio of two effects indicates how many times one effect is greater (or smaller) than the other effect.
* \( p < .05 \). ** \( p < .01 \).
On the problem solving scale, all three groups also achieved significant learning gains, with the highest pretest to posttest change of students’ ability on the test (in logits) for the Search for Life group (0.598), followed by the alternative group (0.464) and the Mission to Pluto group (0.415). The Search for Life group achieved a higher increase than did the alternative group and the Mission to Pluto group. Compared to the Mission to Pluto group, the odds for success on problem solving were 44% higher in favor of the Search for Life group and 12% higher in favor of the alternative group, as indicated by the ratios of treatment effects, 0.598/0.451 = 1.44 and 0.464/0.415 = 1.12, respectively. On the other side, the ratio of treatment effects for the Search for Life group versus the alternative group (0.598/0.464 = 1.28) indicates that the odds for success on problem solving were 28% higher in favor of the Search for Life group.

The comparison of treatment effects across scales shows that the Search for Life group and the alternative group gained more in content understanding (0.660 and 0.645, respectively) than in problem solving (0.598 and 0.464, respectively). The opposite was true for the Mission to Pluto group. The students in that group did slightly better in problem solving ($\eta = 0.415$) than in content understanding ($\eta = 0.385$).

**Discussion**

The results from this study indicate that the materials developed for the Astronomy Village project can be used effectively to promote interdisciplinary understanding and problem solving in planetary science within a relatively short period of time. The treatment effects for all three treatment groups were statistically significant on each scale, content understanding and problem solving. The two largest treatment effects are attributed to the Search for Life students and the alternative group students on content understanding. The results are not surprising for the alternative group students, since they studied the content for both Search for Life and Mission to Pluto. This demonstrates the effectiveness of the background materials available in Astronomy Village. However, even though the Search for Life students studied half as much content as the alternative group, they improved slightly more than the alternative group on the content understanding test. The Search for Life students also did better than the alternative group students on the problem solving test. There are two primary conclusions that can be drawn from these findings. First, students in the Search for Life group investigated the existence of water on other planets. In some cases, this involved image analysis of planetary surfaces. These results indicate that the knowledge students developed in Search for Life transferred to their ability to solve Mission to Pluto problems, as well. Second, these results support the recommendation of the *National Science Education Standards* that students should study fewer topics in-depth using an inquiry-based approach. Student inquiry activities focusing on developing content understanding and problem solving will result in knowledge that is transferable (National Research Council, 1996).

The Mission to Pluto students had statistically significant improvement on both content understanding and problem solving. These results demonstrate that the Mission to Pluto activities are effective at helping students learn important content. However, the gains for the Mission to Pluto students on both subscales were lower than the gains for the other two treatment groups. There are two factors that may have contributed to this result. First, the Mission to Pluto investigations (described in the Method section) focused on cratering, volcanism, and plate tectonics. These processes are only tangentially related to core requirements for life on a planet. Therefore, there was little information in the Mission to Pluto investigations that would transfer to Search for Life problems. Had the Mission to Pluto investigations focused on atmospheric processes and presence of liquid water, there may have been greater transfer.

Second, Mission to Pluto students performed better on problem solving than on content understanding. In the Mission to Pluto investigations, the students spent a great deal of time on learning how to interpret remote sensing images of planetary features and how to infer underlying processes. It is possible that there were not a sufficient number of activities helping students develop the conceptual understanding of planetary processes. Prior research has demonstrated the importance of well-organized content understanding for success at problem solving (Shin, Jonassen, & McGee, in press; Hong, et al., 2001). It seems that the amount of content understanding may place a limit on the extent of transfer of problem solving skills to a related set of topics.

This study focused on alternative uses of technology for promoting conceptual understanding and problem solving in planetary science. The results of this research are consistent with other research on the use of technology in education. Although technology can be effectively used to present information to students, it is more effective when designers take advantage of the interactive nature of the technology to engage students in inquiry (Kozma, 1991; Jonassen, 1996).
Within the Search for Life Core Research Project, students developed conceptual understanding through interactive, inquiry-oriented image analysis activities. This approach fostered a greater understanding of both the concepts and problem solving related to planetary science than the other two approaches. Within the Mission to Pluto Core Research Project there was more of a focus on problem solving. Students did not develop as strong in conceptual understanding. The fact that the content-only alternative treatment group outperformed the Mission to Pluto group on problem solving provides insight on the importance of conceptual understanding for successfully engaging in problem solving. In conclusion, the results in this study indicate that effective uses of technology in the classroom will leverage the interactivity of technology to engage students in the development of conceptual understanding through inquiry activities.

References


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Appendix

Example Items From the Astronomy Village Assessment Instrument

This appendix contains example items from the Astronomy Village assessment instrument. There are two items that require complex content understanding and two items that require problem solving. For each pair of items, one item relates to Search for Life and the other item relates to Mission to Pluto. An asterisk indicates the correct answer.

Complex Content

If a planet has a thick atmosphere, you would expect to see

a) distinct craters such as those seen on the Moon or Mercury.
b*) few craters such as those seen on Earth or Venus.
c) broad, shallow craters.
d) broad, deep craters.
e) narrow, deep craters.

Why do scientists believe that if life forms exist elsewhere in our solar system, the life forms will likely be very small?

a) Most living things on Earth can only be seen with a microscope.
b) Nature gives smaller organisms better protection than larger ones.
c*) Smaller organisms are less complex than larger ones and have fewer energy requirements.
d) If organisms were large, such as a large animal, they would have probably been discovered by now.

Problem Solving

![Figure 1. Image 1: Surface of Edina.](image)

Edina is the eighth planet in a solar system orbiting an imaginary star. The diameter of Edina is about 1/3 that of Earth. Image 1 of Edina was taken by a satellite orbiting the planet. The canyon structure in the image suggests that

a*) in the past, Edina's climate has been warmer and wetter.
b) samples of rocks from Edina would contain radioactive elements.
c) Edina was formed through accretion.
d) Edina must currently have water.
Which of the following statements is most likely true about the imaginary planet Pagano (based on Image 2)?

a) The surface of Pagano is composed mainly of sedimentary rock.
b) Pagano has a cold, inactive core.
c*) Pagano has winds on the surface that have eroded the rocks.
d) Pagano has many desert areas but not many mountainous areas.