Discovery learning, representation, and explanation within a computer-based simulation: finding the right mix

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Abstract

The purpose of this research was to explore how adult users interact and learn during an interactive computer-based simulation supplemented with brief multimedia explanations of the content. A total of 52 college students interacted with a computer-based simulation of Newton’s laws of motion in which they had control over the motion of a simple screen object—an animated ball. Two simulation conditions were studied, each differing in how the feedback of the ball’s speed, direction, and position was represented: graphical feedback consisted of animated graphics and textual feedback consisted of numeric displays. In addition, half of the participants were given simulations supplemented with brief multimedia explanations of the content modeled by the simulation in order to investigate how to promote referential processing, a key component of dual coding theory. Results showed significant differences for both the use of the explanations and simulations containing graphical feedback in helping participants gain both implicit and explicit understanding of the science principles.

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1. Introduction

Physics has long been regarded as one of the most abstract and difficult subjects to learn. A common belief is that the students who do well in physics have a special aptitude for learning science and mathematics. It is easy to understand how many might believe that the only students who are going to “need” physics are
future engineers and physicists. However, instead of reserving physics for a gifted few, many feel that technology offers the chance to change commonly held perceptions about who can or should learn physics (White & Frederiksen, 1998). For example, complex systems such as physics can easily be modeled on desktop computers. Computer simulations make complex systems accessible for students of varying ages, abilities, and learning levels. The computer, instead of the student, can assume responsibility of processing the underlying mathematics in order to let the student begin exploring a complex system by first focusing on conceptual understanding (de Jong & van Joolingen, 1998; Penner, 2000–2001; Roschelle, Kaput, & Stroup, 2000). The emphasis of this approach is on experiences, rather than explanations, of a domain. Of course, this is not to suggest that explanations are not important. Indeed, much current research points to the advantages of multimedia explanations for learning (Mayer, 2001). However, the interactive affordances of computer simulations and other modeling environments suggest an educational model based on experiential learning. The role, timing, and influence of explanations while learning science principles need to be reconsidered and reexamined.

Despite the enthusiasm for educational simulations, many challenges to the effective design of simulations remain. Among the most difficult are questions about the design of a simulation’s interface (Edwards & Holland, 1992; Schneiderman, 1998). For example, designers currently can include a wide range of visual, textual, and aural elements in the development of simulations. As the range of available design options increases, so too does the complexity of design decisions. One of the most important considerations in a simulation’s interface design is how to provide meaningful feedback to the user. Cognitive psychologists have long regarded feedback as a critical source of information to assist learners in restructuring their knowledge and supporting their metacognitive processes (Bransford, Brown, & Cocking, 1999; Kulhavy & Wager, 1993). Given the range of ways computers can represent feedback in a simulation, research is needed to ensure that design decisions are made based on the psychological needs of the individual user and not simply on what the computer is capable of doing.

Much research demonstrates that the way information is represented matters greatly in the learning process, at least for memory tasks (Clark & Paivio, 1991; Paivio, 1990, 1991; Sadoski & Paivio, 2001). Research indicates that pictures are superior to words for remembering concrete concepts (Sadoski & Paivio, 2001). Among the various theories that have been proposed to explain this, Paivio’s dual coding theory appears to have the strongest empirical support (Anderson, 1978; Paivio, 1990, 1991; Sadoski & Paivio, 2001). Dual coding theory divides cognition into two processing systems—one visual and one verbal. Although the research supporting dual coding theory is based almost exclusively on evidence derived from supplementing printed text with visuals (including paired associative tasks) (e.g., Sadoski, Goetz, & Avila, 1995; Sadoski & Paivio, 1994), this theory also holds promise in guiding research in computer-based multimedia environments (Mayer, 2001; Mayer & Sims, 1994; Rieber, 1996).
Dual coding theory predicts three separate levels of processing within and between the visual and verbal systems: representational, associative, and referential. Representational structures (either visual or verbal) are formed depending on the nature of incoming information (i.e., visual and verbal information from the environment triggers the visual and verbal systems, respectively). Associative processing leads to connections constructed within either the visual or verbal systems, whereas referential processing leads to connections made between the visual and verbal systems. Referential processing is particularly important because dual coding theory predicts that learning will be enhanced when information is encoded in both systems (i.e., dually coded). Information that is dually coded has twice the chance to be retrieved and used (Kobayashi, 1986). Instruction that promotes dual coding has obvious advantages.

Our past research has shown that the way feedback is represented also matters when learning from simulations of physical science concepts and principles (i.e., laws of motion). Participants increased their implicit knowledge of physics when they interacted with a physics simulation given graphical feedback, but they were unable to demonstrate increased explicit understanding based on the way the feedback was represented (Rieber, 1996; Rieber & Noah, 1997; Rieber, Noah, & Nolan, 1998; Rieber et al., 1996). Implicit understanding was measured by participants’ performance in a game-like activity whereas explicit understanding was measured using a traditional performance test (i.e., multiple-choice question format). The increase in implicit learning given graphical feedback indicated that representational and associative processing occurred almost exclusively within the visual system. Participants’ difficulty in acquiring explicit understanding of the physics principles modeled by the computer was attributed to the highly interactive nature of the discovery-based simulation. Simulations that model physical phenomena (such as physical science) may not provide the learner with sufficient time or guidance for interpreting the continual stream of feedback by both the visual and verbal systems. In other words, the “video game-like” quality of the simulation may have interfered with referential processing by only promoting processing in the visual system and discouraging processing in the verbal system.

The purpose of this study was to investigate ways to facilitate or enhance referential processing as a user interacts with a computer simulation. Our previous research used a pure discovery-based approach—no instruction was included or embedded in the simulation. While highly experiential open-ended simulations appear beneficial in many ways, they do not seem to adequately promote reflection of the science principles. Reflection is an important component for referential processing. One way to promote reflection is to provide the student with a brief explanation of the scientific principle being modeled by the simulation after the student has had an opportunity to interact with the simulation, but not yet master the content of the simulation. In this study, five short multimedia explanations (brief text and simple animation) were embedded throughout the simulation. Each multimedia explanation focused on one of the fundamental physics principles modeled in the simulation. Such a use of alternative representations is consistent with the research on multiple representations (Ainsworth, 1999). Multimedia explanations,
such as these, serve to complement the student’s simulation experience by focusing attention on the specific scientific principle at work. The multimedia explanations should also help to constrain the student’s interpretation of their experience with the interactive simulation so as to help them focus on only the most germane principles of the physics being modeled. Hence, these brief explanations should help the student to organize their interactive experiences by helping them to make meaning from the feedback generated by the simulation, an essential step on the road to understanding (Mayer, 1989).

It was hypothesized that supplementing the simulation with multimedia explanations of the content would facilitate all three types of processing predicted by dual coding theory for explicit learning. Also, since previous research suggests the apparent dominance of the visual system during a user’s interaction with simulations similar to these, it was also hypothesized that the embedded explanations would promote more referential processing when participants were given graphical instead of textual feedback.

Several data sources were used in this study. Traditional performance measures (e.g., question-based pretests and posttests) were used to assess participants’ explicit understanding of the science principles modeled in the simulation. However, such formal tests do not assess other levels of understanding that are embedded in a task. For example, bringing a car to a smooth controlled stop requires an extensive understanding of many motion principles. However, this understanding remains situated in the act of driving—the individual may not be able to explicitly describe the physical relationships at work. Although we recognize that a learner’s ability to transfer conceptual understanding from one task to another (such as to a posttest) remains an important indication of learning, this study also used a measure of implicit understanding found useful in our earlier research. Participants were asked to complete the simulation in a game-like context. Since an understanding of the motion principles is necessary to be successful at the game, the game score provides an alternative data source useful when compared with the participants’ scores on traditional performance measures.

2. Methods

2.1. Participants

A total of 52 junior and senior undergraduate students participated in this study. These participants were enrolled in an introductory computer education course. Participation was voluntary, though extra credit in the course was provided to students as incentive to participate. The average age of all the participants was 21.6 years. The participants were predominately female (90.3%).

2.2. Materials

The materials consisted of a computer-based simulation of Newton’s laws of motion. Participants had direct control over the motion of a simulated, free-floating object (called simply a “ball”). The simulation was presented in a game-like
context with the goal of moving the ball to a specific screen location (called the “target”). All 52 participants were given a total of 30 trials. It was anticipated that as participants gained mastery of the game, they would become bored unless the challenge was increased. Therefore, for the first 20 trials all participants merely had to guide the ball to the target. However, in the final 10 trials, all participants had to guide the ball to the target and bring the ball to a stop while inside the target.

Participants were able to move the ball in two dimensions. They controlled the motion of the ball by pressing one of four screen buttons that applied an impulse force to it, similar to a “kick”, in one of four directions: left, right, up, or down. The magnitude of the force, or kick, did not vary. No other forces (e.g., gravity and friction) were included in the simulation. The computer calculated the resulting motion of the ball (i.e., position, speed, and direction) and reported this information back to the user in real-time. When the ball reached the edge of the screen it was programmed to “wrap around” to the other side of the screen, similar to a video game. For example, if the ball moved off of the right-hand side of the screen as it moved to the right, it would then instantaneously appear on the left edge of the screen (at the same vertical position) still moving to the right at the same speed. The computer calculated the motion of the ball about as fast as the user interacted with the simulation, similar to a video game. The computer provided this information to the user in one of two ways, either as graphical feedback or as textual feedback. Graphical feedback contained a graphic of the target and an animated graphic of the ball while textual feedback consisted of numerical readouts of the screen positions of the ball and target. Half of the participants were given graphical feedback and the other half textual feedback. Examples of these two forms of feedback are illustrated in Figs. 1 and 2.

Participants were also randomly assigned to one of two levels of explanation (yes, no). Explanation consisted of five separate explanatory frames that explicitly described the motion principles using a combination of text and animated graphics. The five frames were presented in sequence, one explanation frame after every two simulation trials (e.g., explanation frame 1 after simulation try 2, explanation frame 2 after simulation try 4, etc.). Therefore, each of the five explanation frames was presented three times throughout the simulation trials. Half of the participants were given these explanations and half were not. An example of one of the explanations is illustrated in Fig. 3.

2.3. Dependent measures

2.3.1. Pretest/posttest of principle learning

A 20-item test was used to measure participants’ explicit understanding of Newtonian motion principles. The questions were designed to test for rule-using learning outcomes (i.e., principles) (as defined by Dick, Carey, & Carey, 2001). In other words, the questions measured the participants’ ability to apply the principles of Newtonian motion in relatively simple situations. Multiple-choice questions (one answer and four distractors) were used as the testing format. Representative ques-
Internal consistency reliability of this test, as measured by the Kuder–Richardson formula 20 (KR-20), was 0.85.

2.3.2. Game score

The time, in seconds, taken by participants to successfully complete the game was used as a scoring feature. A participant’s score for any one simulation trial was equal to the number of seconds elapsed at the moment the game was completed. Each trial had a time limit of two minutes. If time ran out before the participants successfully completed the game, the computer automatically signaled the end of the simulation and a score of 120 was recorded for that try.

2.3.3. Interactivity

The total number of times participants clicked either the “right”, “left”, “up”, or “down” button during each simulation was recorded by the computer.

2.3.4. Frustration

After each simulation trial, participants were asked to rate their level of frustration on a scale of 0 to 8 where 0 was “no frustration”, 8 was “extreme frustration”.

Fig. 1. Snapshot of the computer screen during the simulation in which graphical feedback was provided. Feedback about the ball’s position was displayed by animating the ball on the computer screen.

Fig. 4. Internal consistency reliability of this test, as measured by the Kuder–Richardson formula 20 (KR-20), was 0.85.
2.4. Procedures

The computer administered all of the simulation conditions and testing. Participants were randomly assigned to one of the four conditions (i.e., visual or textual feedback representation with or without embedded explanations) as they reported to the computer lab. The computer immediately administered the 20-item pretest of principle learning. Participants were then given two practice trials with the simulation as an orientation to the task. Participants then were given a total of 30 attempts with their respective simulation condition with or without embedded explanations. After each simulation try, the computer surveyed participants on their level of frustration. Immediately upon completion of the simulation activities, the computer automatically administered the posttest consisting of the same 20 multiple-choice items. Approximately, one hour was needed to complete the experiment.

2.5. Design

This study used a $2 \times 2$ factorial design involving two levels of two between-subjects factors: feedback representation (visual, verbal) and explanation (yes, no). Statistical procedures included a repeated analysis of variance (ANOVA) on the
pretest/posttest of principle learning measuring participants’ application of simple Newtonian principles and separate ANOVA tests on each of the remaining dependent measures. In a repeated ANOVA, statistical significance of differences in pretest and posttest scores on each of the independent variables is achieved by analyzing the interaction between the pretest/posttest of principle learning (within-subjects factor) and each of the independent variables (between-subjects factors; i.e., feedback representation and explanation).

3. Results

3.1. Pretest/posttest of principle learning

Percentage means and standard deviations are contained in Table 1. A significant interaction was found between the pretest/posttest of principle learning and explanation, $F(1, 48) = 9.55, p < 0.01, \text{MSE}_{\text{error}} = 190.51$. The difference between the pretest and posttest scores was greatest when participants were provided with embedded explanations than when they were not given the explanations. There was also a significant interaction found between the pretest/posttest of principle learn-
Fig. 4. Two representative questions from the pretest/posttest of principle learning. (The correct answer to the top question is “4” and the correct answer to the bottom question is “3”.)
ing and feedback representation, $F(1, 48) = 5.0$, $p < 0.05$, $M_{\text{error}} = 190.51$. The difference between the pretest and posttest scores was greatest when participants were provided with graphical feedback than when they were provided with textual feedback. A follow-up multiple comparison of the four posttest means was conducted using Tukey’s studentized range test in order to test for the additive effects of the explanations combined with graphical feedback. Results showed a significant difference between the four means, $F(3, 48) = 4.4$, $p < 0.01$, $M_{\text{error}} = 409.2$. Participants given both graphical feedback during the simulation and the embedded explanations scored significantly higher (mean = 93.5%) than all other groups (mean = 71.9%), as illustrated in Fig. 5. Participants given graphical feedback combined with embedded explanations attained near mastery on the posttest.

### 3.2. Game score

A significant main effect was found for feedback representation, $F(1, 48) = 46.2$, $p < 0.0001$, $M_{\text{error}} = 223974.9$. Participants given graphical feedback scored better on the gaming activity than participants provided with textual feedback. This result is also consistent with previous research. Participant’s level of implicit learning was facilitated more with graphical feedback than textual feedback. However, no significant differences were found for explanation: explicit information about Newton’s laws of motion did not affect participants’ game scores in any way.

### 3.3. Interactivity

No main effects or interactions were found for explanation or feedback representation. Participants’ frequency of interactivity (i.e., mouse clicks) was similar for all participants in all treatment groups.

### Table 1

Mean percentage scores and standard deviations for principle learning

<table>
<thead>
<tr>
<th>Feedback representation</th>
<th>Principle learning</th>
<th>Pretest</th>
<th>Posttest</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$M$</td>
<td>55.0</td>
<td>93.5</td>
</tr>
<tr>
<td></td>
<td>SD</td>
<td>18.6</td>
<td>9.0</td>
</tr>
<tr>
<td></td>
<td>$N$</td>
<td>13</td>
<td>13</td>
</tr>
<tr>
<td>With embedded explanations</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Graphical</td>
<td>$M$</td>
<td>47.7</td>
<td>74.2</td>
</tr>
<tr>
<td></td>
<td>SD</td>
<td>27.1</td>
<td>28.0</td>
</tr>
<tr>
<td></td>
<td>$N$</td>
<td>13</td>
<td>13</td>
</tr>
<tr>
<td>Textual</td>
<td>$M$</td>
<td>55.8</td>
<td>65.4</td>
</tr>
<tr>
<td></td>
<td>SD</td>
<td>17.9</td>
<td>24.9</td>
</tr>
<tr>
<td></td>
<td>$N$</td>
<td>13</td>
<td>13</td>
</tr>
<tr>
<td>Without embedded explanations</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Graphical</td>
<td>$M$</td>
<td>54.2</td>
<td>76.2</td>
</tr>
<tr>
<td></td>
<td>SD</td>
<td>18.8</td>
<td>12.4</td>
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<tr>
<td></td>
<td>$N$</td>
<td>13</td>
<td>13</td>
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<tr>
<td>Textual</td>
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<td>$N$</td>
<td>13</td>
<td>13</td>
</tr>
</tbody>
</table>
3.4. Frustration

A significant main effect was found for feedback representation, $F(1, 48) = 12.9$, $p < 0.001$, $MS_{\text{error}} = 2501.2$. Participants provided with graphical feedback were significantly less frustrated than participants provided with textual feedback. However, there was no main effect for explanation: the presence or absence of the explanation did not affect participants’ frustration levels.

4. Discussion

The purpose of this research was to investigate ways to facilitate or enhance an individual’s learning of physics principles while interacting with a computer simulation based on an experiential approach. Many facets of learning were studied in this research, such as implicit versus explicit understanding as well as patterns of interactivity and frustration. While computers afford the design of highly interactive open-ended learning environments such as simulations, decisions about how to design the interface of a simulation are often made with little understanding of how the user will perceive, process, and interpret the resulting feedback that the simulation provides. This study was designed to explore the effects of some of the most basic interactive attributes of simulations on cognition. In addition, this study examined the role, timing, and structure of explanations, one of the core elements of instructional design, as a way to support student learning within the experiential approach. Participants were given succinct multimedia explanations intermittently while working with the simulation. It was believed that the embedded explanations...
offered the means of enhancing referential processing without seriously interrupting the interactive nature of the simulation (as would a complete tutorial). They were designed to help participants reflect on their interactive experiences with the simulation by directing their attention to the most salient or germane aspects of the science principles underlying the simulation.

This research was guided by dual coding theory that predicts more and effective learning should result when information is encoded both visually and verbally and if connections are made between these visual and verbal codes (Paivio, 1990; Sadoski & Paivio, 2001). Information that is dually coded doubles the chance for retrieval since learners have two ways to access the information. According to dual coding theory, these connections are established through referential processing. However, there has been little application of dual coding theory to simulations and other interactive learning environments. The highly interactive nature of many computer simulations creates an interesting dilemma. On one hand, the experiential nature of an educational simulation is very compelling—users often become very active and engaged in a simulation, similar to the experience of playing a video game. However, the intense and demanding interactivity of many simulations may not provide adequate time for the user to carefully reflect on the principles being modeled by the simulation. Without sufficient guidance or time and opportunity for reflection, referential processing may not take place. Therefore, while the simulation may lead to successful implicit learning (i.e., success at completing the simulation activities), the simulation may actually hinder or interfere with explicit learning. This research tried to gain insight into this issue by studying the influence of the way a simulation’s feedback is represented when combined with embedded explanations.

Participants’ performance on the test of principle learning of Newtonian motion (explicit learning) was greater when the feedback in the simulation was represented graphically (consisting of continually updated animated graphics) than when the feedback was represented textually (consisting of a continually updated numerical display). Likewise, participants scored higher on the simulation’s gaming activity (implicit learning) when given the graphical feedback during the simulation. Similarly, the embedded explanations were very successful aids to explicit learning even though they were exceedingly brief (one frame each). Participants who were given the explanations gained significantly more explicit understanding of the science principles than those who were not given the explanations as measured by the test of principle learning of Newtonian motion. Not too surprisingly, the explanations were of little help to participants as they played the game: participant game scores were the same regardless of whether they were given the explanations.

Of most interest is the result that when participants were given feedback represented graphically and brief multimedia explanations, they outperformed all other participants on explicit learning of the physics principles. These additive effects suggest that, from a dual coding perspective, the explanations in tandem with the simulations promoted representational, associative, and referential processing. When participants were given both graphical feedback and explanations they reached near mastery on the posttest (average score of 93.5%). These results suggest an interest-
ing approach to optimizing the experience of learning by simulation. Unlike traditional approaches where simulations are usually used as follow-up practice activities to tutorials (see, for example, Alessi & Trollip, 2001), it may be possible to center learning on the highly interactive and experiential nature of a simulation. Certainly, there seem to be cognitive advantages to students making meaning through personal discovery and exploration. Every “secret” they discover, recognize, and articulate becomes their knowledge, not someone else’s. Of course, the promise of personally constructed knowledge comes with increased responsibility on the part of each learner. Computer simulations afford learners with the chance to interact with information-laden representations of complex domains (e.g., physics, mathematics, chemistry, history, etc.). In many simulations, students face the burden of making meaning from a continual stream of information about the physical properties of screen objects. These results suggest a way to supplement a simulation to help students meet the difficult task of learning in a simulation. Students effectively used both the interactive simulations using visual representations and brief multimedia explanations to make sense of the complex scientific information.

Although dual coding theory was the theoretical basis for this research, cognitive load theory offers a complementary theoretical framework for understanding learning from multimedia (Mayer & Moreno, 2002). According to this theory, the limits of working memory impose serious challenges to learning (Kirschner, 2002; Sweller, 1994). If the memory demands of a task exceed the limits of working memory, then learning will not occur. Learning the laws of motion require the student to not only grasp individual concepts and principles, but also successfully to relate them to other principles (e.g., the relationship between acceleration and velocity in one and two dimensions). If the demands of the content and the task exceed a person’s capacity to manage the information and these interrelationships, the person will not be able to process it adequately and little or no learning will occur. When learning Newtonian mechanics, understanding the interrelationships of concepts and principles is very challenging. While a simulation offers students the opportunity to interact with a working model of these ideas, they frequently become disoriented or unable to focus on the most essential cues. Giving students brief multimedia explanations intermittently helps them to quickly organize their experiences with the simulation, helping them to construct appropriate schemata of the physics content. In the parlance of cognitive load theory, this approach leads to germane cognitive load (Kirschner, 2002). In contrast, instructional designers may be tempted to provide students with extensive tutorials along with the simulations. Although such an approach “covers the content”, it can often result in instructional “overkill” which can easily overwhelm students’ cognitive capacity. This study suggests an approach that shows the benefit of well-designed, well-timed, and well-placed multimedia explanations situated in an experiential approach afforded by computer simulations. Discovery learning within a simulation can be very inefficient, ineffective, and frustrating to students, but providing students with short explanations at just the right time can offset these limitations.

Recent discussions of cognitive load theory suggest adding metacognitive load to the theory (Valcke, 2002). Do students, especially novices in a domain, know which
representations and learning experiences offer them their best chance for learning? As an informal follow-up to the quantitative study reported here, we tried to gain insight to this question by asking other adults who are physics novices to go through the same physics materials used in this study while we observed and interviewed them. The only difference was that we gave these students free and total access to both the explanations and simulations. When left to decide on their own, we found that physics novices clearly did not want formal explanations when using these physics materials, even though most said they recognized the benefits that the explanations offered. They tended not to use the explanations much because they did not see them as an aid in achieving greater success at the game even though they knew they were going to be tested on their physics understanding at the end of their session. In other words, students with little prior knowledge in a domain do not necessarily make good decisions when it comes to their own learning. The phenomenon of students not choosing to select options from which they clearly could benefit is reminiscent of the research on learner control (Clark, 1982; Milheim & Martin, 1991; Steinberg, 1989). These metacognitive decisions are crucial to a student’s success, especially given the popularity of constructivist uses of simulations (de Jong & van Joolingen, 1998). Constructivist orientations to technology generally favor more open-ended curricula where the teacher’s role is to facilitate and guide student discovery in the learning environment. The question of when the teacher should intervene to coach, counsel, or teach has long remained an open and contested question. The results reported here underscore the importance of this decision. This study also shows how such instruction can be off-loaded to the technology without changing the experiential nature of the learning. Of course, the explanations offered by a master teacher at just the right time for a student should offer much richer opportunities for reflection than the five embedded multimedia explanations studied here.

It is important to note the task specific nature of the visual representation of feedback produced by a computer simulation. A conclusion of this study is that different representations will lead to different outcomes for certain tasks and not that graphical feedback is generally “better” than textual feedback for all tasks. The design challenge is to match the demands of the task with appropriate representations. Certainly, the graphical feedback in this study was very consistent with learning about the laws of motion. However, as we continue to follow up this work with other participants in informal qualitative sessions, we have observed an interesting phenomenon—many often come to prefer the textual feedback after gaining sufficient expertise and success with the simulation and game. The reason for this is simply that they look for ways to increase the challenge by developing their own creative strategies.

Finally, a brief discussion of the results of the remaining dependent measures deserves mention. The lack of main effects on interactivity is in contrast to that found in previous research (Rieber, 1996; Rieber et al., 1996). Previous research found that participants interacted far less when given graphical feedback even though their game scores were better. This difference is probably due to the simpler nature of the simulation and backs up the hypothesis that participants often increase their level of overt interactivity when disoriented (users seem to revert to
“frantic clicking”). The result of participants reporting more frustration when given verbal instead of graphical feedback is consistent with our previous research. Graphical feedback is much preferred by participants in physics simulations of this type. The relationship between imagery and motivation is also consistent with dual coding theory (Clark & Paivio, 1991).

Several questions for future research remain. More research is needed on the effects of the visual and verbal elements of the embedded explanations so as to better understand how they interact with different feedback representations in the simulation. Also, more precise information on the contribution of the embedded explanations versus the simulation experience is needed. That is, the issue of how much learning is taking place just by having participants view the explanations without participating in the simulation is open to question. Future research should also expand on the delicate demands of optimizing challenge to maintain motivation in game-like activities embedded in a simulation (Dempsey, Lucassen, Gilley, & Rasmussen, 1993–1994; Lepper & Malone, 1987; Randel, Morris, Wetzel, & Whitehill, 1992) and the use of certain games as measures of implicit knowledge.

We also believe that this research would benefit from qualitative data, such as observation and interview of participants as they complete the simulations, due to the explanatory power of rigorous qualitative methods.

In conclusion, the results of this research point to a simple yet powerful means of facilitating referential processing in a simulation. The use of very brief multimedia explanations of the content modeled by a simulation coupled with appropriate matching of the simulation’s feedback representation to the task appears to be a surprisingly effective way to guide students to focus on the most important principles in the simulation without subverting personal discovery or risking decreased motivation.

References


