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Distributed Cognition in a Sixth-Grade Classroom: An Attempt to Overcome Alternative Conceptions about Light and Color

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Abstract

In this study, we discuss the scaffolded design of ODRES (Observe, Discuss, and Reason with Evidence in Science), a computer tool that was designed to be used with elementary school children in science, and report on the effects of learning with ODRES on students' conceptual understandings about light, color, and vision. Succinctly, dyads of sixth-grade students were engaged in distributed collaborative inquiry regarding the scientific concepts of light, vision, and color in order to solve a mystery problem about a stolen diamond. ODRES was employed to scaffold students' collaborative inquiry with different tools, such as the simulator that simulates the effects of the color of a light source on an object, the magnifying glass that enables students to make careful observations, and the notebook that organizes the results of students' investigations. Students performed two cycles of collaborative inquiry, and each cycle was followed by a classroom discussion where students could present their solutions, share information, reflect, raise questions, and get feedback about their proposed solutions. The results showed that learning with ODRES positively affected students' understandings and promoted a lasting effect on their conceptions. Moreover, the results provide useful guidance about how ODRES can be used as a learning tool in collaborative inquiry, and explain the role of discussion and investigation of inquiry processes at the level of a distributed cognitive system. Implications for designing distributed educational systems for children are finally discussed. (Keywords: distributed cognitive system, collaborative inquiry, computer-assisted learning, distributed cognition, conceptual change, science learning.)

INTRODUCTION

Teachers often get frustrated when their students, including their best ones, do not comprehend fundamental science concepts taught in class. Students' failure to understand science concepts is often attributed to alternative conceptions, preconceived notions, non-scientific beliefs, naive theories, or conceptual misunderstandings which interfere with subsequent learning (Clement, 1982; Driver, 1983; Glaser & Bassok, 1989; Hewson, Hewson, & Bekett, 1984; McCloskey, 1983; Resnick, 1983; Wiser, 1989).

In view of the fact that alternative conceptions can have a detrimental effect on student learning, researchers have invested intensive efforts during the last 30 years in identifying students' alternative conceptions in nearly every domain of science (Eaton, Anderson, & Smith, 1984; Confrey, 1990; Kikas, 2004; Nesher, 1987; Valanides, Nicolaidou, & Eilks, 2003; Valanides, Gritsi, Kampeza, & Ravanis, 2000; Valanides, 2001). Consequently, they attempted to design, develop, and implement teaching methods to break down alternative conceptions and facilitate learners' conceptual understanding and growth (Duit & Treagust, 2003; Osborne, Driver, & Simon, 1996). For example, teaching strategies include identifying alternative conceptions before correcting them (Hake, 1992), helping students to confront their alternative conceptions (Brna, 1988), using cognitive conflict to promote conceptual change (Limon, 2001), and making use of demonstrations (Katz, 1991), concept maps (Arons, 1990; Minstrell, 1989; Okebukola & Jegede, 1988), analogies (Duit, Roth, Komorek, & Wilbers, 2001), or computer simulations (Linn, 2003; Stratford, 1997).

While the impact of studies relating to learners' conceptions on educational research and practice is impressive, conceptual change in science remains a perennial problem. Many alternative conceptions continue to appear in students and adults, even after receiving instruction focusing on dislodging them (Clement, 1987; McCloskey, 1983). Since many science conceptions are deep seated and resistant to change, they interfere with subsequent learning, and, therefore, further research efforts in this area would be quite useful and important.

In this paper, the study of alternative conceptions in science is grounded in the theoretical notions of distributed cognition. This framework situates the study of learners' conceptions in the social matrix of a learning environment, where students are engaged in shared cognition activities mediated by technological tools, artifacts, and others (Hutchins, 1995a; Nardi, 1996; Salomon, 1993). Using the framework of distributed cognition and its focus on the propagation of information, coordination of activities, and negotiation of meaning among different individuals and artifacts/tools, it becomes possible to reconsider methodological issues related to research concerning alternative conceptions, and move the study of learners' conceptions beyond the individual cognitive level (i.e., descriptive ideas located in the individual mind before, during, and after instruction) to the systems level taking into consideration social aspects of cognition. Specifically, the research questions that this study sought to answer were:

(a) How does conceptual change emerge in a distributed learning environment; and

(b) What are the variables that may hinder a distributed cognitive system to function optimally?

We begin with a discussion of the framework of distributed cognition, and then we describe the context of the study, the tool used, and data collection and analysis methods. Next, we present and discuss the results, and we conclude with final reflections about the design of effective distributed learning environments for facilitating the understanding of scientific concepts, as well as thinking about complex problem-solving tasks.

DISTRIBUTED COGNITION

New ideas about the nature of cognition and learning, such as distributed cognition and other situative approaches (Brown, Collins, & Duguid, 1989; Cobb, 1994; Greeno, 1997; Greeno, Collins, & Resnick, 1996; Lave & Wenger, 1991), deserve a closer look in regard to how they can be used to deeply re-examine some of the perennial problems in education, such as learners' alternative conceptions in science. A main tenet of distributed cognition is that cognition is distributed across the individual, other persons, and tools. Distributed cognition views groups (people and tools) as a cognitive system (Dalal & Kasper, 1994) and attempts to describe "group mechanisms with concepts borrowed from individual cognition (e.g., group memory, shared understanding, group regulation etc.)" (Dillenbourg, 2006, p.155). Distributed cognition theorists view cognition not as an exclusive property of individuals, but as distributed or "stretched over" an extended cognitive system, which may include the individual, other people, artifacts, and tools (Hutchins, 1990, 1991, 1995a, 1995b; Pea, 1993; Salomon, 1993). In the distributed cognition framework, computer technologies are not considered as mere conveyors of information, but as cognitive tools and partners in cognition that share some of the cognitive burden among individuals when carrying out tasks (Hutchins, 1995b; Salomon, 1993; Salomon, Perkins, & Globerson, 1991). The distribution of cognition across people and cognitive tools, and the propagation of knowledge and collaboration that occur within the extended cognitive system act as scaffolds within an individual's zone of proximal development enabling the individual to accomplish tasks that are beyond his or her own capabilities when working alone.

Flor and Hutchins (1991) further explained that distributed cognition is an alternative and rich way to examine the representation of knowledge both inside the heads of individuals, and among different individuals, tools, and artifacts. Therefore, within the distributed cognition framework, different units of analysis can be adopted in order to describe a range of cognitive systems. For example, one can focus on the processes of an individual mind, on an individual mind in coordination with a set of tools, or on a group of individuals in interaction with each other and even with a set of tools.

The implications of distributed cognition for the design of learning environments to overcome learners' conceptions in science are significant, as the framework provides a methodological approach to re-examine and rethink conceptual change in science. In particular, most research studies on conceptual change have focused almost exclusively on describing the cognitive performance of subjects at different ages and at different levels of expertise, and they rarely focused on understanding how various contextual and situational variables can promote conceptual change (Vosniadou, Ioannides, Dimitrakopoulou, & Papademetriou, 2001). Since the early 1990s, there exists ample evidence indicating that concepts are embedded in rich contexts, and in the interaction of people with tools and artifacts (Barab & Hay, 2001; Linn, Bell, & Hsi, 1998; Linn & Hsi, 2000). From this perspective, conceptual change can most certainly be initiated and mediated by social and cultural processes. For this reason, research on conceptual change must move ahead to also examine the role of situational and cultural variables, such as, the learning task, the social interactions, and the tools and artifacts as critical components of the learning environment. This perspective does not exclude the cognitive processes of the individual mind, because the framework of distributed cognition allows not only a consideration of the role of contextual variables and group processes, but also the examination of the mental processes of the individual mind not in isolation, but in relation to other variables in the learning situation.

ALTERNATIVE CONCEPTIONS ABOUT LIGHT AND COLOR

Due to the property of light to travel from one point to another instantly and invisibly, light phenomena cannot be experienced directly, and individuals limit their explanations to mere descriptions of what they can only see and experience. Consequently, their conceptual understanding of light phenomena is severely impeded because of light's high degree of abstractness. Computers may prove to be valuable tools in providing virtual experiences that can help students experience light phenomena and correct any alternative conceptions they may construct out of their everyday experiences. This was the impetus for developing ODRES, a computer tool that was designed to help students overcome alternative conceptions about light, such as: (a) color constitutes an exclusive property of an object and consequently remains unchanged; and (b) when colored light illuminates a colored object, the color of the light mixes with that of the object.

For example, only a small percentage of elementary students can explain correctly how a source of light affects the color of objects (Shapiro, 1994). The results of a research study conducted by Eaton et al., (1984) showed that after instruction, only 4% of the students explained correctly how a source of light affected the color of objects. Similarly, research findings by Anderson and Karrqvist (1983), Guesne (1985), and Galili and Lavrik (1998) indicated that most students believe that color is unrelated to light and constitutes a permanent characteristic of objects. Furthermore, Wanderslee, Mintzes, and Novak (1994) showed that student alternative conceptions about light and color are deeply engrained and resistant to traditional or expository instruction.

Understanding how light relates to color is contingent upon understanding (a) that white light is a compound entity, (b) how different frequencies of white light are absorbed or reflected, and (c) the mechanism of vision. Thus, it would seem backwards to develop instruction for light and color, prior to developing instruction for understanding the compound nature of white light, light's absorption and reflection, and the basic mechanism of vision. However, taking into consideration the complexity of the subject matter, we judged that it would be more effective to develop a computer tool that could be used not only as a diagnostic tool for identifying students' alternative conceptions about light and color, but also as a tool for challenging learners' alternative conceptions about light and color. It was evident from our discussions that the design of an appropriate computer tool should follow the tenets of constructivist learning, and provide affordances for presenting discrepant events that could create cognitive puzzlement or dissonance, as well as examining the effects of these activities on learners' existing conceptions. Obviously, we were not interested in any complex explanation of the relationship between color, light, and vision, but we were mostly interested in promoting an understanding that the color of an object is not an exclusive and permanent property of the material, and that the color of an object changes depending upon the color of the light that illuminates it.

Such a shift in learners' understanding of light and color could then serve as the starting point for introducing more complicated concepts, such as the concept of white light as a compound entity, and for providing scientific explanations about the interaction of matter and light.

THE DESIGN OF ODRES

ODRES was designed and developed in several cycles of prototypes during the period of 2003–2005. ODRES stands for **O**bserve, **D**iscuss, and **R**eason with **E**vidence in **S**cience, and it is designed around the inquiry cycle of conducting observations, recording and organizing data, discussing with others, drawing conclusions, and reasoning with evidence about a phenomenon.

Its design was informed by several guidelines proposed in the literature by different researchers (e.g., Linn, 2003; Linn, Davis, & Bell, 2004; Quintana, Soloway, & Krajcik, 2003; Reiser, 2004). Succinctly, the design framework was guided by the following principles: (a) Situate learning in a rich and authentic context, so that students feel motivated to learn in this context; (b) Provide information in multiple representations (textual, visual, auditory, etc.), so that the needs of different learners can be satisfied; (c) Make the process of inquiry explicit to the learners by providing scaffolds to structure the inquiry process and decompose the complexity of the task; (d) Use representations that students can employ to observe important properties of the data; (e) Use representations that students can employ to test initial conceptions and hypotheses, and (f) Use scaffolds (reflection prompts, questions, etc.) to make learners' thinking explicit.

Moreover, research evidence indicates that when students work in small groups, they learn how to integrate ideas better and develop a coherent conceptual understanding about scientific phenomena (e.g., Bereiter & Scardamalia, 1992; Brown & Campione, 1994; Linn, Davis, & Bell, 2004; Rogers & Newton, 2001; Songer, 1996), and so ODRES was designed to also support collaboration.

In this study, collaboration when working with the computer tool was restricted to dyads of primary school students. When learners first launch ODRES, they type in their names, so that the software can provide a personalized learning session and also keep track of user information in log files. After that, a motivating problem-solving scenario about a stolen diamond is presented to them, and they are asked to assume the role of a detective to solve the mystery. Based on the story, Dr. Devon, a collector of diamonds, invited four of his best friends, namely, Leo White, Aris Blue, Marc Green, and Peri Red, to have dinner in his mansion and look at the new diamond he recently acquired. In this scenario, the surnames of the four guests indicated the corresponding color of the shirts they were wearing. This was a deliberate design decision in an attempt to minimize the cognitive load of students' working memory.

Dr. Devon was very proud of his diamond collection and kept his diamonds in his house in three different rooms, each lit with a different color of light, so that he and his friends could examine and admire the diamonds under different light conditions. The three rooms were lit with red, green, and blue light, and, because of this, they were called the red room, the green room and the blue room, respectively. Dr. Devon was living in his mansion with his butler and the guard of the house. The latter employee was mainly responsible for the security of the house and especially for the safety of the diamond collection. For this reason, there were security cameras all over the mansion for surveillance and close watch of the people visiting it.

That night, Dr. Devon welcomed his four good friends in his home and invited them to admire "White Angel," the new diamond he recently added to his collection. He also encouraged them to examine the diamond under the different light conditions that existed in each of the three rooms. After doing so, the four guests had dinner with Dr. Devon and then left. Before long, Dr. Devon decided to check on his diamond collection once more before retiring for the night, and at that time, he announced to his employees that "White Angel" was stolen and had been replaced by a fake one. Dr. Devon and his employees tried together to understand how this could have happened, but they could not find any solution. Based on the recordings of the security cameras, a person was observed alone in the three different rooms, but his face could not be recognized because he was wearing a hood. Thus, Dr. Devon decided to report the theft to the police and ask for their help. From that point on, students are asked to assume the role of a police detective and use different tools afforded by the software to conduct investigations in order to find out who stole the diamond. Users can choose to assume the role of Zack Costello, a male detective, or Melinda Brown, a female detective.

As mentioned above, according to what the surveillance cameras showed, a person was seen in the three different rooms of the house but his face could not be recognized because he was wearing a hood. Also, because of the different light conditions that existed in each room, the color of his clothes appeared different every time. Of course, this information provided important evidence that students could find useful for solving the mystery. In essence, it was expected that careful examination of this information would gradually help the learners to abandon the idea that the color of an object is an exclusive and permanent property of the object (i.e., the thief's shirt), and that the color of an object depends on the color of the light illuminating it.

After the students are presented with the mystery problem and the guard's testimony, the software scaffolds students' problem-solving processes by providing them with a number of tools in order to conduct investigations and solve the mystery. In essence, different scaffolds are provided to help students engage in a systematic inquiry process of making observations to collect evidence, forming and testing hypotheses, discussing points of view with their partners, and integrating their ideas to form an evidence-based explanation. For example, students can use the simulator to simulate the effects of the color of a light source on each guest's shirt. The simulator is an important tool as it tests students' hypotheses and provides immediate feedback in the form of a visual representation demonstrating that the color of a light source illuminating a colored object may modify the color of the object in specific and consistent ways.

When students use the simulator, they first drag and drop the figure of one guest at a time in each one of the three virtual rooms in the simulator (i.e., the

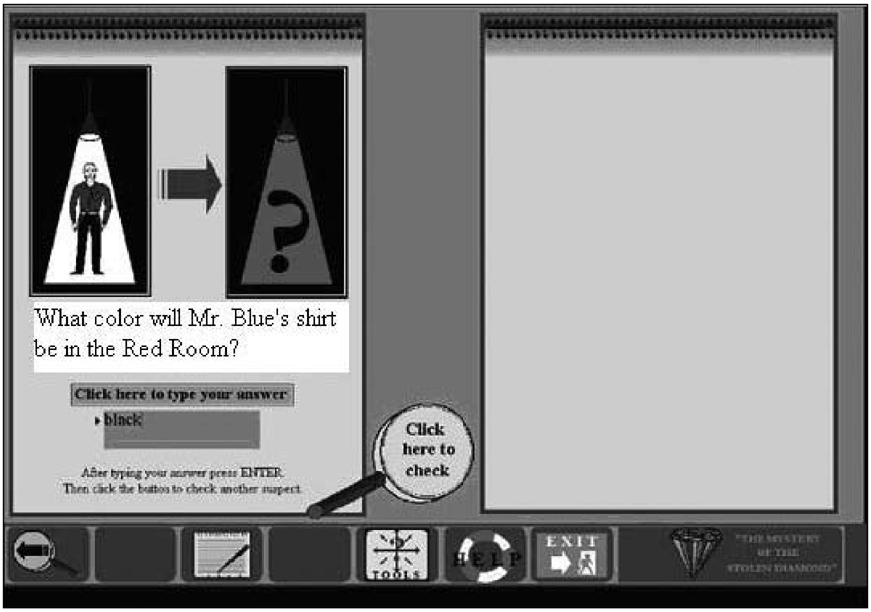


Figure 1: Forming and checking a hypothesis about the effects of the color of a light source on the color of an object.

green, red, and blue rooms), and then, as shown in Figure 1, they are asked to write a hypothesis of what they think will happen to the color of the guest's shirt. After they write their initial conception, the tool simulates the effect and shows the respective outcome. Students continue testing and revising their initial conceptions with the simulator.

The result of each investigation is automatically recorded in a matrix. When the matrix is filled, it appears as it is shown in the upper part of Table 1. Stu-

Table 1: Results from Students' Investigations with the Simulator and Information Provided by Camera Recordings in each Version of the Software

	Room		
	Red	**Green**	**Blue**
Guest's shirt color as shown by the simulator			
Peri Red	red	black	black
Leo White	red	green	blue
Marc Green	black	green	black
Aris Blue	black	black	blue
Guest's shirt color as shown by the security cameras in each version of ODRES			
First version	red	green	blue
Second version	red	black	black
Third version	black	green	black
Fourth version	black	black	blue

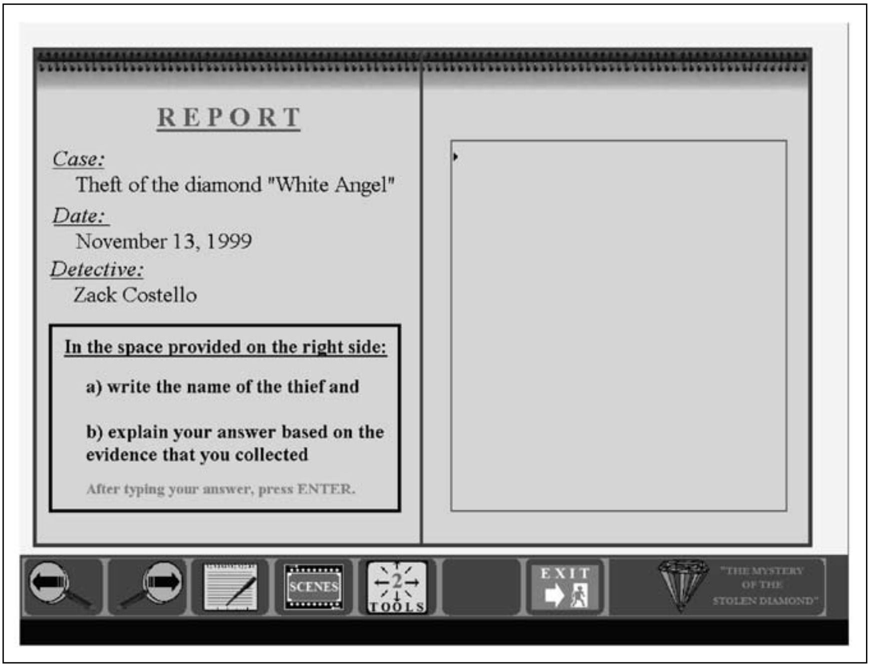


Figure 2: Writing an evidence-based explanation.

dents can use the matrix as an external memory device to organize their observations in a cohesive manner, extract patterns from the data, and propose a well-informed solution to the mystery.

Specifically, as shown in Figure 2, the software prompts students to write down the name of the thief and an evidence-based explanation for the results of their first investigation. Then, the software informs the students that a classroom discussion facilitated by the teacher will follow, so that they have an opportunity to present their solutions to others, share information, reflect, raise questions, and get feedback about their proposed solutions.

During the classroom discussion, students are challenged about their proposed solutions, and they are asked to more carefully examine the collected evidence and re-evaluate their conclusion. They turn to their computers again to search for new evidence or re-evaluate old evidence. They find that they can use a new tool, namely, the magnifying glass, to carefully look for details that they may have failed to consider previously, and that might be important to consider. Students are told that this is important to do, because a good detective has a moral obligation to critically examine all relevant evidence before any final conclusion, so that he does not victimize innocent people. Thus, students use the magnifying glass, shown in Figure 3, to carefully re-examine all previous evidence and make new and more detailed observations. For example, students need to consider all information that is available to them, and to search for more and detailed evidence or additional clues that may help them to be as much confident as possible about the identity of the thief, by avoiding any mis-

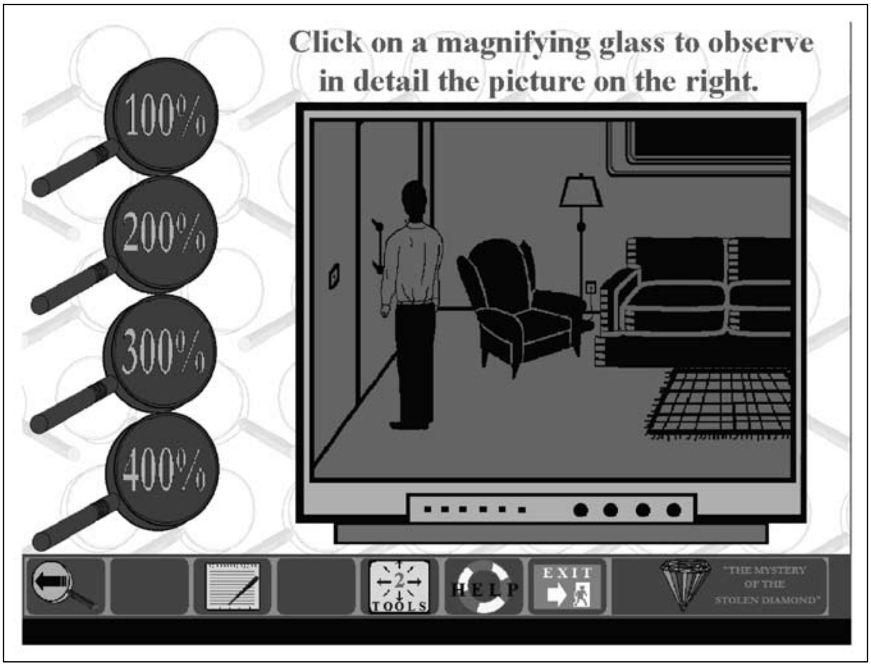


Figure 3: The magnifying glass.

leading information. Then, in light of new evidence, students are asked again to propose a new solution to the problem and to discuss it in class with others.

Different versions of the software have been developed in order to promote independent student work and eliminate plagiarism. In the various versions, the clothes of the seven characters, that is, the four guests (Leo White, Aris Blue, Marc Green, and Peri Red), Dr. Devon, the butler, and the security guard, are the same. Specifically, Leo White has a white shirt on, Aris Blue a blue shirt, Marc Green a green shirt, Peri Red a red shirt, Dr. Devon a white shirt and a red bowtie, the security guard has a red shirt on with black buttons on the collar, and the butler a white shirt with a blue bowtie. All characters wear black trousers. However, the recordings of the surveillance cameras in each version of the software provide data that incriminate a different person. Moreover, it was expected that each version of the software would engage students in deep cognitive thinking in order to reason with evidence about their proposed solutions for the mystery problem. The lower part of Table 1 shows information related to the color of each thief's shirt in the three rooms of the house, as shown by the security cameras in each version of the software.

For example, in one version of the software the thief was the owner of the mansion who fabricated the theft of his diamond in order to get money from the insurance company. Thus, he conspired to victimize his friend Leo White by taking off his black coat, but unfortunately (for him), he forgot to remove his red bowtie, which was identified under the magnifying glass and was used as evidence against him. In another scenario, the thief was the guard of the mansion who tried to take advantage of his knowledge about surveillance cameras, but neglected to take into consideration that under a magnifying glass one could identify the buttons on his collar that constituted evidence supporting the innocence of Peri Red. In another scenario, the thief was the respectable butler of the mansion whom Dr. Devon trusted immensely, as he had been working for his family for many years. Thus, the butler thought that it could be very easy to avoid any suspicion against him, because all the information collected from the camera recordings would incriminate Leo White. Contrary to his expectations, a smart detective could use a magnifying glass to observe that the thief was wearing a white shirt and a blue bowtie. Evidently, the different versions of the software were designed and developed in such a way that all seven people who were in the house that night could be considered as potential suspects.

METHODOLOGY

Participants

Eighteen 11-year-old students from an intact sixth-grade elementary school classroom participated in the research study. The sixth-grade classroom was selected randomly from three other sixth-grade classrooms that existed in the school. The school was also selected randomly from seven other schools for which we had permission from the Ministry of Education to visit and conduct research studies. The 18 students were from the same class (it was a small class of 18 students). The teacher did not participate in any of the research procedures. She helped us with setting up the classroom, she introduced us to the students, and she then let us conduct the study. Prior to the study, we visited, of course, the teacher and we explained to her what we wanted to do. She was excited about giving her students an opportunity to work in such an environment, but she told us that because she did not have any experience with teaching in a technology-enhanced environment she did not want to teach the lesson—she wanted us to do it, so she could learn.

Of the 18 participants, 11 were females and seven were males. According to the classroom teacher, the academic performance of four students was rated high, the academic performance of 10 students was rated medium, and the academic performance of the remaining four was rated low to very low. Students were randomly divided into nine dyads—three dyads were of homogeneous ability and six of heterogeneous ability. As shown in Table 2, two of the three homogeneous dyads (dyads 4 and 6) were of medium ability and the other (dyad 5) of low ability. The composition of the heterogeneous dyads varied across the three achievement levels as shown in Table 2. Most students had previous but limited experience with computers, either in their school computer lab or in their homes, while some of them had no experience whatsoever.

Research Instruments

Two researcher-made tests were used to assess students' ideas about the relationship between light and color. One test was used both as a pre-test and post-test, and another as a retention test. The pre-test was administered three days before the actual study took place and the same test was administered again as

Table 2: Information About the Students in Each Dyad

Dyad	Members	
1	S1* [H]**	S4 [M]
2	S10 [M]	S18 [H]
3	S17 [L]	S16 [M]
4	S11 [M]	S8 [M]
5	S12 [L]	S15 [L]
6	S5 [M]	S6 [M]
7	S14 [M]	S3 [H]
8	S9 [M]	S2 [L]
9	S7 [H]	S13 [M]

* *S1..S18 designate the 18 students in the classroom.*

** *Letters H (High), M (Medium), and L (Low) in brackets signify the academic achievement level of each student.*

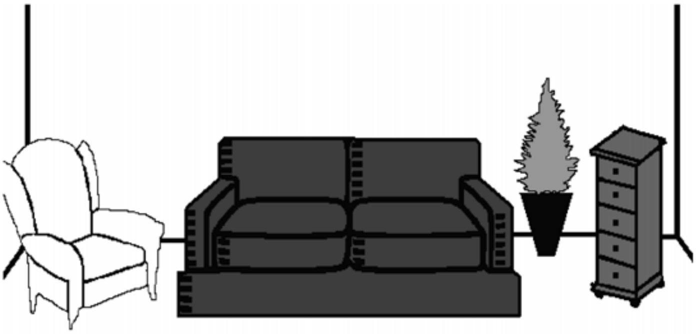
a post-test after the completion of the study, that is, three days after the pre-test was administered. Each administration lasted approximately 20 minutes. For validity, we gave the tests (they were all very similar) to three experts, who conduct research in science teaching and learning as well as in the assessment of science learning, to evaluate the extent to which the tests could capture students' conceptions about light and color. The experts advised us on several aspects and after a few iterations of revisions they reached consensus. After this first step, for reliability purposes, we gave the tests to five students to pilot test the clarity of instructions. Based on their responses, we made very few minor changes on the wording of the instructions, and we then used the instruments in our study.

In the pre-test and post-test, students were presented with a picture depicting a room lit with white light (sunlight) and in which seven items were shown. The seven items were: (a) a blue couch, (b) a white armchair, (c) a red cabinet, (d) a black flower-pot, (e) a green plant inside the black flower-pot, (f) white-colored walls, and (g) a white-colored floor. Then, students were told to assume that the same room was lit with a different light color and were asked to decide whether the color of the objects would be different. They were also given colored pencils to appropriately color the objects in the picture, and in addition, to explain and justify their thinking, as it is shown in Figure 4 (p. 320).

Student ID: --

Date: --------------------------------------

1. Assume that the room you see below is lit with white color.



2. Now, assume that the **room above is lit with blue light**. You are asked to use the colored pencils provided to you, to color each object in the picture below, and explain at the back of this page your reasoning.

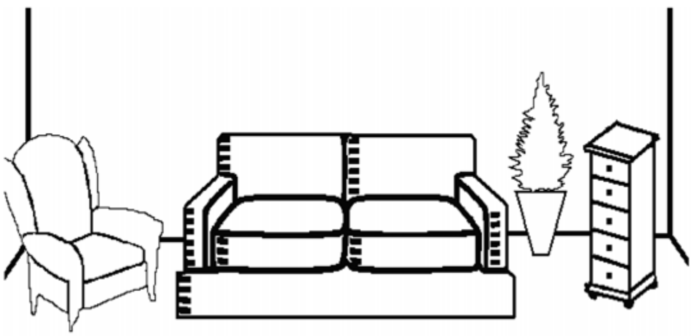


Figure 4: The pre-test and post-test.

Three different versions of the pre-test were administered, one in which students were told that the room was lit with blue light, another in which the room was lit with red light, and a third version in which the room was lit with green light. This constituted an attempt to minimize the possibility of students copying from each other, as no students sitting next to each other were given the same version of the test. Students received one point for each item in the picture that they correctly colored, provided that they also wrote a correct justification for each answer. Thus, scores on the pre-test ranged from 0 to 7. At the end of the study, the three versions of the same test were administered as post-tests, but it was made certain that no student received the same version of the pre-test as a post-test.

The retention test was administered three months after the post-test. Students had no other lessons related to light, vision, and color after the administration of the post-test. The retention test was slightly different from the first test in terms of the objects depicted in the picture, but the two were structurally isomorphic. Specifically, students were given again the picture of a room, lit with white light (sunlight), which had (a) white-colored walls, (b) a white-colored floor, (c) a black box, (d) a white box, (e) a red box, (f) a green shelf hanging on the wall, and (g) a blue cabinet. Then, the students were told to assume that the same room was lit with a different light color (i.e., blue, green, and red), and were given colored pencils to appropriately color the objects in the picture. In addition, students were also asked to write down reasons for their decisions. Three different versions of the retention test were also used and a rotating system with the different colors was adopted, so that no student used a light source of the same color in any of the three testing situations. The retention test was administered in 20 minutes and the same range of scores (0 to 7) was used. In the three testing conditions, students worked individually (not in dyads).

Research Procedures

The study took place in an intact sixth-grade elementary school classroom during a science lesson. In the classroom, there were no computers and nine laptop computers were brought in, one for each dyad. The dyads were seated in a Π configuration, and no two dyads adjacent to each other worked with the same version of the software. Students in their dyads first worked with the software for 60 minutes. Then, they were asked to participate in a classroom discussion that lasted 20 minutes and was facilitated by the first author of this paper. During the discussion, the facilitator asked students to name the thief and to justify their conclusion. The facilitator listened to students' proposed solutions and asked them to work with the software for 25 more minutes in order to look for new evidence confirming or disconfirming their claims. This new investigation was justified on the ground that any detective should avoid victimizing innocent people by re-evaluating the collected information and continuously searching for new evidence. Then, the facilitator engaged students in a second discussion that lasted 15 minutes. In the second discussion, students presented their new solutions or supported their initial solution with new evidence. Thus, during the two discussion sessions, the facilitator only listened to what students had to say and, in the first discussion, encouraged them to look for more evidence in order to back up their claims.

Data Collection Methods and Analyses

A mixed method approach was used to collect both qualitative and quantitative data. Qualitative data were collected to document the discourse of the students in each dyad interacting with each other and with the computer tool, and the discourse during the two classroom discussions. Qualitative data also included information from video cameras and observation/field notes from two other researcher-participants. The two researcher-participants offered technical assistance to the students when they needed it, and also observed students interacting with each other in the dyads. Each researcher-participant spent at least five minutes observing a dyad before moving to another. Particularly, the researchers made observations about the role of each learner in the dyad, and how much help each dyad asked from the researchers. The field notes were used to mostly enhance and better interpret the transcripts from the videotaped sessions. For videotaping purposes, 10 cameras were used—one camera for each dyad, and another for capturing the classroom interactions. Also, data related to students' interactions with ODRES, for example, learners' hypotheses and explanations, were automatically saved by the software in log files. Additionally, quantitative data related to students' performance were collected with the pre-test, post-test, and retention test. Also, qualitative data were collected with the three tests regarding the explanations students provided about their reasoning.

All videotaped sessions were transcribed and then analyzed from a systems perspective (Ackoff & Emery, 1972). The unit of analysis was a distributed cognitive system composed of the two individuals in each dyad interacting with each other and with ODRES. The main focus of the analyses was to analyze the interactions in the distributed cognitive system, to identify how and why a joint cognitive system as a whole performed, and to identify variables that might have hindered the joint cognitive system to function optimally.

RESULTS

Students' Performance on the Pre-test, Post-test, and Retention Test

Scores on the pre-test ranged from two to five, indicating that none of the participants answered correctly all test items. The mean was 4.11 and the standard deviation was .83. Scores on the post-test ranged from three to seven, indicating that, after using ODRES, there were students who answered correctly all test items, and that a general progress was observed towards more correct conceptions. The mean was 5.17 and the standard deviation was 1.29. A *t*-test for paired samples was conducted and it was found that the difference between participants' performance on the pre-test and the post-test was statistically significant, $t = -4.24$, $p < .01$.

Three months after the post-test was administered, students were given the retention test to complete. Scores on the retention test ranged from three to seven, indicating that three months after the intervention students expressed exactly the same ideas as those they expressed on the post-test, and thus they had exactly the same performance on the retention test as that on the post-test. These results relate however only to students' final performance and do not really show conceptual change of those students, who, despite the fact that they changed their initial conceptions they did not construct totally correct conceptions. For example, the majority of the students clearly indicated that the color of an object was not an exclusive property of the object and that it depended on the light illuminating it. But, they were not able to state correctly the outcome of the interaction between light and the color of the objects.

A qualitative analysis (Patton, 2002) of the reasons students gave in support of their answers revealed a hierarchy of different groupings, showing that the students constructed different alternative ideas about the effects of the color of a light source on the color of objects. Specifically, there was a group of students who did not express consistent ideas or did not follow the instructions on the tests (Category F). Some other students suggested that the color of objects always takes the color of the light source (Category E). For example, if a room is lit with red light, then all objects in that room will become red. Light was considered as having material existence and "could cover all the things in the room." Other students, forming three different subgroups, had the idea that the color of a light source affects the color of objects in various ways. Some insisted that only objects with white color always take the color of the light source, but the other objects keep their initial color (Category D). In reality, these students did not consider "white" to be a color. Other students proposed that white-colored objects take the color of the light source, while those objects having the same color as the light source keep their color, and objects with different color (including the black color) take a color that is a combination of their initial color and the color of the light source (Category C). Another group of students had similar ideas, but insisted that objects with black color remain unaffected without recognizing, of course, that such an outcome was related to the property of "black color" to absorb all frequencies of white color (Category B).

Table 3 (p. 324) presents the distribution of students in the different categories of responses for each one of the three tests and shows how students' ideas changed across the three tests. These categories can be considered as constituting a hierarchy, which consists of different levels of conceptual understanding and which shows progressively from Category F to Category A the development of more scientifically correct conceptions about the relationship between color and light.

In Table 3, the number before the letter S indicates the number of the dyad a specific student participates in, and the number following the letter S indicates an individual student. Figure 5 (p. 325) shows the performance of each student, across the three tests, sequentially from dyad 1 to dyad 9. Thus, a quick comparison of students' performance in each dyad is easily obtainable. The numbers from 1 to 6 on the Y axis indicate sequentially the six categories of conceptual understanding from F (1) to A (6), as shown in Table 3.

The results in Table 3 and Figure 5 clearly indicate the following: (a) four students (S5, S8, S12, and S15) expressed incorrect and inconsistent ideas across the three tests or they did not follow the instructions given to them. Interestingly, two of them (S12 and S15) were from the same dyad (dyad 5) and their academic performance was rated as low or very low. (b) Six students (S1, S2, S7, S9, S13, and S17) had incorrect, or partially correct, but consistent ideas, across the three tests. Students S7 and S13 were from the same dyad (dyad 9). (c) Two students (S4 and S16) from different dyads expressed the idea on the pre-test that objects with black color take a blended color, but on the post-test and retention test they stated that objects with black color remain unaffected by the color of the light source. (d) One student (S11) from dyad 4 stated consistently during the post-test and the retention test that every object takes the color of the light source. Students in dyad 4 initially did not follow the instructions. (e) Five students (S3, S6, S10, S14, and S18) stated consistently, both on the post-test and the retention test, correct conceptions, although their conceptions were

Table 3: Categories of Students' Responses on each One of the Three Tests

	Pre-test	Post-test	Retention test
	Students	Students	Students
• **Category A** (They answered all test items correctly.)		7**S3** 7**S14** 2**S10** 2**S18** 6**S6**	7**S3** 7**S14** 2**S10** 2**S18** 6**S6**
• **Category B** (Only objects that have white color take the color of the light source and objects with the same color as the light source keep their initial color. Objects with different color than the light source take a blended color, but objects with black color remain unaffected.)	2**S10** 2**S18** 7**S14**	1**S4** 3**S16**	1**S4** 3**S16**
• **Category C** (Only objects that have white color take the color of the light source, and objects with the same color as the light source keep their initial color. Objects with different color than the light source, including the black color, take a blended color.)	*1S1* 1**S4** 3**S16**	*1S1*	*1S1*
• **Category D** (Only objects that have white color take the color of the light source. Other objects keep their initial color.)	6**S6** *8S9* *3S17*	*8S9* *3S17*	*8S9* *3S17*
• **Category E** (Every object always takes the color of the light source.)	*8S2* 7**S3** 9S7 *9S13*	*8S2* 4**S11** 9S7 *9S13*	*8S2* 4**S11** 9S7 *9S13*
• **Category F** (Students expressed inconsistent ideas or did not follow the instructions.)	4**S11** *4S8* *6S5* *5S12* *5S15*	*4S8* *6S5* *5S12* *5S15*	*4S8* *6S5* *5S12* *5S15*

Note: Italics indicate students that expressed the same ideas across the three tests. Bold letters indicate changes from pre-test to post-test.

incorrect on the pre-test. Four of these students came from dyads 2 and 7, and one from dyad 6, and their performance was rated as medium (S6, S10, and S14) or high (S3 and S18).

These results indicate that students did not always change their ideas and, in some cases, they continued to exhibit incorrect conceptions about the concepts

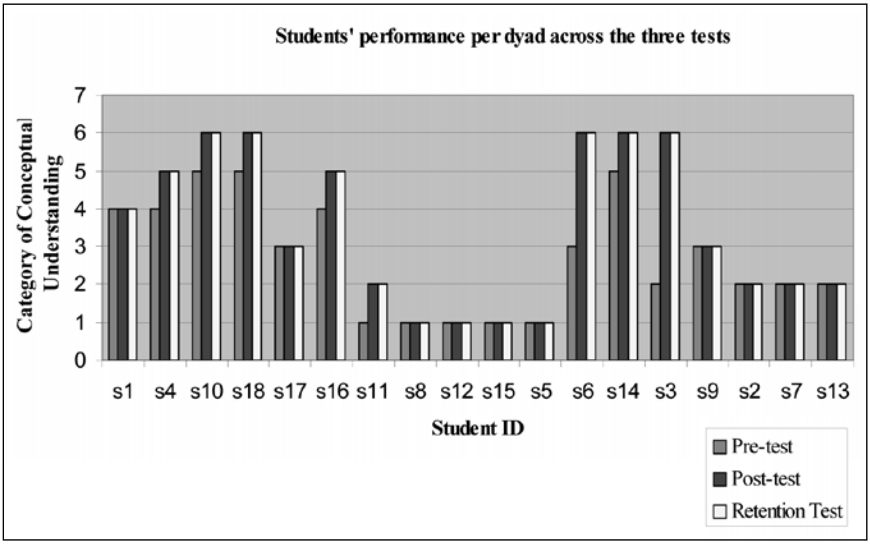


Figure 5: A graphical representation of students' performance on the three tests in sequence from dyad 1 to dyad 9.

of light and color. The results also indicate that students from the same dyad, who initially had either similar or different conceptions, did not always exhibit the same understanding about the effects of the color of light on the color of different objects. For example, the results displayed in Figure 5 and Table 3 indicate that four of those five students who consistently expressed correct ideas on the post-test and the retention test worked in the same dyads, that is dyad 2 (S10 and S18) and dyad 7 (S3 and S14). However, that was not always the case. For example, student S5, a member of dyad 6, performed poorly (Category F), whereas student S6 from the same dyad was among the five most successful students. There were also other students who despite the fact that they belonged in the same dyad, they (a) performed differently on the post-test and retention test, although they had the same performance on the pre-test, for example students S4 and S1 from dyad 1, and students S8 and S11 from dyad 4; (b) had the same performance on the post-test and retention test, although they had different performance on the pre-test, such as students S14 and S3 from dyad 7; and (c) had different performance on the three tests, such as students S2 and S9 from dyad 8, and students S16 and S17 from dyad 3. The overall results from this analysis provide initial evidence indicating that member interaction and collaboration differed among dyads.

Students' Interactions Between Them and With ODRES

A qualitative analysis of the transcripts from a systems perspective was carried out to investigate how students' interactions between them as well as with ODRES contributed to each dyad's performance. The analysis focused on five different aspects of the whole process, namely: (a) getting familiar with the interface of the tool, (b) using prior knowledge to solve the problem, (c) recognizing and managing cognitive conflict, (d) hasty and unjustified conclusions, and (e) reaching an evidence-based explanation.

Getting familiar with the interface of the tool

At the beginning, students in each dyad spent considerable time trying to understand how to use ODRES. Students' discourse revealed that they were not very familiar with computers and, consequently, they struggled with the interface of the system. For example, students S1 and S4 (dyad 1) felt unsure about which buttons to click on and persisted in asking the researchers for assistance.

S1: Sir, do we need to click here?
Researcher: (No answer. He pretends that he is busy.)
S4: Click here.
S1: No.
S1: Sir, do we need to click here?
Researcher: Yes.
S1: Sir, what should we choose here?
Researcher: Please concentrate on your task and you will figure things out.
S1: Should we click here?
Researcher: [no reply]
S4: No, not here.
S1: Sir, we clicked here and it did not continue.
S4: Click again.
S1: Hmm, now it did it.

Students S14 and S3 also had difficulties with the interface of the tool. In part, this could also be attributed to the design of ODRES, because the interface of the system did not support learning in joint action, which means that only one student at a time could use the mouse to click. This resulted in a lack of coordinated actions between the students in the dyads.

S3: What do we need to do? Where do we need to click? Let's click here.
S14: You cannot click there. Wait.
S3: I do not care, I will do it.
S14: Wait, wait. It has to give you the arrow first and then you can click.
S3: Oh yeah?
S14: Now you can click.
S3: [He clicks constantly different buttons without reading first]
S14: Wait, we need to read first - do not push the buttons so fast.

These excerpts clearly indicate that students argued about what buttons to click or not, and these conclusions were also confirmed from the video recordings, which also showed that some students even expected their partners to allow them to use the mouse for most of the time, because they did not have an opportunity before to work with laptop computers. As we will clarify later, students' excitement to work with the computers did not always contribute to an improvement in their conceptual understanding.

Using prior knowledge to solve the problem

The results indicated that students initially relied on their prior knowledge in order to solve the problem. For example, students S1 and S4 (dyad 1) used their knowledge about mixing paints of different color to form initial hypotheses about the effects of the color of a light source when illuminating a colored object.

S1: We have dropped the guy with the blue shirt in the red room. What would the color of his shirt be?
S4: That would give us purple. I will show you.
S4: Sir, can I have colored pencils?
Researcher: Yes, sure. Why do you need them?
S4: I want to color something.
[S1 and S4 use a blue color pencil to color a white piece of paper and then on top they colored it again with the red pencil.]
Researcher: What do you think it will happen?
S4: The new color will be purple.
Researcher: So, is this your hypothesis?
S1 and S4: Yes!!
Researcher: Ok, now you can check with the simulator and find out whether you are correct.

These dialogues stress the implications of prior knowledge on any subsequent learning, because existing conceptions act as intuitive screens through which any new experience is explained, and provide direct support to constructivist approaches of teaching and learning. Evidently, these students insisted that the rules for mixing paints and crayons applied also in the case of mixing the color of a light source with the color of an object.

Recognizing and managing cognitive conflict

After forming initial hypotheses, students used the simulator to check their validity. In those cases where the simulated outcomes confirmed students' initial ideas, they simply carried on with their investigations. In those cases where the simulated outcomes provided evidence contradicting students' hypotheses, students either changed their initial ideas without raising questions or expressing disbelief (students S8 and S11), or they insisted on keeping their first ideas and ignored the outcomes of the simulator (students S16 and S17), which provided contradictory evidence.

S8: What will the color of Mr. Blue's shirt be in the blue room?
S11: Let's read the directions again.
[They are reading the directions]
S8: The color will be black.
S11: No, the color will be blue. Definitely blue.
S8: No white.
S11: Let's check.
[They observe that it is blue]
S8: Ok, it is blue, let's write it.
S11: Let's drop Mr. Blue in the red room.

S8: It will be purple.
S11: No, blue. No, purple. Ok let's check.
S8: Oh, it is black.
S11: Ok, let's write black.

The previous dialogue clearly indicates a passive acceptance of the outcomes of the simulator without recognizing or paying attention to the evidence that was contrary to their expectations. It was thus unclear whether the contradictory evidence created any cognitive conflict in the individual minds of the students. Consequently, ODRES did not function as it was expected and did not help these students to go through the process of managing cognitive conflict that is considered as a prerequisite for conceptual change.

On the contrary, in the following dialogue, student S16 not only insisted on her initial ideas despite the contradictory evidence, but she also managed to persuade S17 to accept her unjustified and irrational conclusions. This is a clear indication that students did not trust the simulator or an indication of the tenacious nature of their existing conceptions. Student S16 considered light to have a material existence and could cover all other things. For instance, every object will take the red color when the color of a light source is red. The dialogue below also shows an excerpt of the discourse in a dysfunctional dyad, where one member, namely S16, who was a female with medium performance and had a very strong character, was inconsiderate of the point of view of the other student, namely S17 who was a female student with very low performance and low profile, and always managed to persuade S17 to accept her opinions.

S16: What will the color of Mr. Blue's shirt be in the red room?
S16: It should be red.
S17: No, yellow.
S16: Red, red.
S17: Yes, ok.
S16: Let's drop Mr. Blue in the red room.
S16: The color of the shirt will be red.
S17: Let's check.
S17: It shows black.
S16: No, no, it is not black.
S17: But, look, it shows black.
S16: It seems black, but it is red.
S17. OK.

Hasty and unjustified conclusions

Students were very enthusiastic about the problem they had to solve, and all dyads except one (dyad 5) were very eager to announce to the researchers the thief of the diamond even before carrying out a single investigation with the simulator. The researcher, as shown in the excerpt below, had to explicitly tell the students that they had to systematically collect evidence, and decide who stole the diamond based on the evidence.

S5: Sir, we know who stole the diamond.
Researcher: Who do you think?

S5: Mr. White.
Researcher: Can you explain why?
S6: Do you also want a reason?
Researcher: Of course, how can you be sure that it is Mr. White?
S6: We are not sure.
Researcher: Have you collected evidence indicating that Mr. White stole the diamond?
S6: No.
Researcher: How do you know then?
S5: It is what we think.
Researcher: That is not enough. You need to collect evidence.
S5: OK.

This dialogue provides evidence indicating that there were students in the classroom who were rushing to hasty and unjustified conclusions and seemed unable to suspend their judgement until they could find evidence to support their conclusions. It seems that students perceived learning with ODRES as a game and they were all rushing to find the solution to win.

Evidence-based explanations

Those students who were able to solve the problem formed explanations based on the evidence they collected. Their statements indicated that they were able to comprehend that color is not an exclusive property of an object, and that when a source of light illuminates a colored object, the color of the light source does not mix with that of the object. However, as the excerpt below shows, students' arguments were based on their sensory experiences or the observable changes of the color of objects. As it was expected, they could not relate the outcome to the nature of white light, the properties of matter, and the mechanism of vision, and it was not expected from them to comprehend that the color of an object relates to the properties of matter to absorb some frequencies (colors) of the compound white light and reflect others that reach the eye, and so decide the color of the object.

Researcher: So, who do you think stole the diamond?
S10: Definitely Mr. White stole it.
Researcher: Are you sure?
S10: Yes, we have evidence to prove it.
Researcher: Can you explain it?
S10: Yes, when somebody wears a white shirt, and enters a room, the color of the shirt takes the color of the room. So, the white in the blue will become blue, in the red will become red, and in the green room will become green. So, it must be Mr. White.
Researcher: OK, but what if the color of Mr. White's shirt was blue?
S10: The blue in blue will remain blue, and in all other rooms black.
Researcher: But, previously you said that the blue shirt in the red room will become red.
S10: Yes, but I was wrong.

Evidence from the Classroom Discussions

When students announced the results of their initial investigations during the first 20-minute discussion, it became clear that despite the fact that eight dyads of students (except dyad 5) reached a conclusion about the thief of the stolen diamond, the explanations offered by some dyads were far from satisfactory. For example, the explanations provided by some dyads of students created doubt as to whether both students in each dyad really understood the effects of a colored source of light on the color of objects. There were cases where the students from the same dyad did not agree or their explanations were far from satisfactory. Evidently, some students needed additional scaffolding, because this was the first time ever that they were studying about light and related phenomena, and they had difficulty in understanding that the color of an object is not a permanent characteristic of the object itself. Moreover, students could not understand why other students in different dyads reached a different conclusion, and seemed rather puzzled by the different proposed solutions. Thus, despite the efforts of the facilitator (first author) to explain that there were different versions of the software incriminating each time a different person, students continued to raise questions indicating their puzzlement.

Finally, they were instructed to re-examine the evidence more carefully and try to find answers to their own questions, but no more scaffolding or further guidance was provided. It was emphasized that the re-examination of the available evidence was necessary, because a detective has a moral obligation to be absolutely sure about the correct identity of the thief before releasing the results of any investigation.

The information from the 15-minute discussion (second discussion) revealed that only three dyads of students changed their proposed solutions and explained that the thief of the diamond had to be the owner of the mansion (dyad 1) or the butler (dyads 5 and 6). There were of course dyads that should not change their proposed solutions, because the thief was really one of the four guests, as students correctly indicated during the first discussion. But, in this latter case, students needed to provide additional evidence and support their conclusions based on evidence they collected using the magnifying glass. It was clear again that the different possible solutions rather puzzled the students instead of promoting their understanding. This can be attributed to the fact that students working with one version of the software could not relate to the evidence that students working with another version were presenting to explain their reasoning, because that information was not available to them. Both discussions were interesting and vivid, but more time and scaffolding seemed to be needed.

DISCUSSION

In this study, we first explained the design of ODRES, a computer tool that was used with elementary school children in science, and we then discussed the effects of learning with ODRES on students' conceptions about light and color. The results showed that there was a significant and lasting change on students' understandings about light and color. Specifically, the results showed significant differences between the pre-test and the post-test, and between the pre-test and the retention test, but there were no significant differences between the post-test and the retention test. Nonetheless, more detailed examination of the results indicated that change in conceptual understanding was restricted only to eight students and that only the students in two dyads, dyad 2 and dyad 7, worked well together. Thus, it seems that the other students who showed evidence of conceptual change were in reality working alone, since their partners showed no evidence of conceptual change and/or understanding.

Based on the results, it seems that better learning outcomes could have been obtained if the dyads were formed in a way so that all students in a dyad were required to equally contribute to the collaboration. The results indicate that the dyads were not functioning effectively, since, for the most part, only one of the two students in each dyad was actively engaged in the learning activity, whereas the other student seemed to be a passive observer. Most importantly, these findings shed light on the nature of distributed collaborative inquiry and identify factors that may impede conceptual change in a distributed computer-enhanced learning environment.

Based on the qualitative results of the study, it becomes evident that effective distributed collaborative inquiry can take place only when the tools supporting the inquiry afford working spaces that allow learners to communicate, share points of view, and organize collaborative work. Such working spaces should allow all individual cognitions to be equally represented so they can be distributed across the extended cognitive system for consideration and evaluation. Failure of educational software systems to host collaborative working spaces can result, as the findings of this study showed, in distributing ideas, coming most probably from the most assertive students in a group, which might not always be correct. Additionally, allowing for all cognitions to be individually represented in the distributed cognitive system enables the systematic examination of the contribution of each participant in the extended cognitive system.

Furthermore, according to the results, the cognitive processes underlying the collaboration and learning of young children in a distributed inquiry environment are not the same as the cognitive processes reported in the literature of distributed cognition of highly skilled experts, such as pilots and air-traffic controllers (Hutchins, 1990, 1991, 1995a, 1995b) who are usually the users of distributed systems. As the results showed, not only young learners have persisting misconceptions, but they also fail to recognize and manage cognitive conflict when it is presented to them. Therefore, the design of educational software for young children should afford scaffolds for helping them to recognize and manage cognitive conflict. Scaffolds for recognizing and managing cognitive conflict can take the form of question and reflection prompts every time a discrepant event is presented to the learners.

Finally, as the findings showed, students were excited to work with ODRES because of its attractive multimedia features. For many students, ODRES was an interesting and playful activity, but not an activity related to learning about light and color. Thus, a third issue that needs to be considered in the design of educational software systems for children is learners' perceptions of the task and how often these need to be taken into consideration. Our judgment at this point is that they should always be considered, because as our data strongly suggest learners' perceptions of the task heavily operate in the learning task as they easily get distributed and are just as viable as other more concept-related cognitions.

Some limitations exist in this research. First, obviously the sample of the study was small. However, it was important for us during this first attempt to use the software in a real school classroom, to keep the sample small so we could collect a lot of data that would allow us to do both quantitative and qualitative analyses. Even with this one classroom with 18 students, the amount of data was tremendous and we spent more than six months analyzing data.

Second, in this study, ODRES was integrated in a classroom where light, color, and other related light phenomena (i.e., light propagation, reflection, refraction, mechanism of vision, etc.) were neither part of the planned curriculum, nor familiar concepts to the students. ODRES was used as a stand alone learning activity independent of the regular classroom activities in an attempt to pilot test its use and effectiveness. For this reason, students did not receive any help or guidance from the facilitator of the session (the first author) who only monitored the two discussions. It would have been much better if ODRES was integrated in a classroom where the subject of light and color was part of the planned curriculum.

Third, the multiple versions of ODRES, and the multiplicity of solutions resulting from them, rather confused the majority of the students and possibly overloaded their working memory to the extent that they were unable to focus on the relevant information. Based on the two discussions in the classroom, it was evident that most of the dyads did not identify additional information after using the magnifying glass either because of limited observational skills, or because the multimedia features of the software captured most of their attention, and thus failed to pay careful attention to the purpose and the procedures of the investigation. Finally, we feel now that it would have been better to form our dyads in a better way (based on individual characteristics), so we could have an empirically informed point of view of the characteristics of a functional dyad.

In conclusion, the framework of distributed cognition proved to be a valuable framework for studying learners' conceptual change at the systems level taking into consideration social aspects of learning. The findings of the study can help teachers in better assessing learning in distributed learning environments, and software designers in designing appropriate computer programs for promoting conceptual change in young learners.

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