Journal of Science Education and Technology, Vol. 16, No. 2, April 2007 (© 2006)
DOI: 10.1007/s10956-006-9034-2

Understanding Scale: Powers of Ten

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The classic film "Powers of Ten" is often employed to catalyze the building of more accurate conceptions of scale, yet its effectiveness is largely unknown. This study examines the impact of the film on students' concepts of size and scale. Twenty-two middle school students and six science teachers participated. Students completed pre- and post-intervention interviews and a Scale Card Sorting (SCS) task; all students observed the film "Powers of Ten." Experienced teachers' views on the efficacy of the film were assessed through a short written survey. Results showed that viewing the film had a positive influence on students' understandings of powers of ten and scale. Students reported that they had more difficulty with sizes outside of the human scale and found small scales more difficult to conceptualize than large scales. Students' concepts of relative size as well as their ability to accurately match metric sizes in scientific notation to metric scale increased from pre- to post-viewing of the film. Experienced teachers reported that the film was a highly effective tool. Teachers reported that the design of the film that allowed students to move slowly from the human scale to the large and small scales and then quickly back again was effective in laying the foundation for understanding the different scales.

KEY WORDS: scale; measurement; technology.

INTRODUCTION

"Those of us who were lucky enough to be in the audience for the designer Charles Eames's 1970 Norton lectures at Harvard, where he showed the original version of his film "Powers of Ten" (1968), will never forget its impact. Moving from galaxy to proton, zooming from the edges of the universe to the hand of a man lying on a picnic blanket in a Chicago park and then into a carbon atom on his hand, the film lends the viewer nothing less than a sense of the proportions of the universe." (Patton, 1999, The New York Times, p. G12)

The essential question of this study is whether or not the film "Powers of Ten" (http://powersof10.com) really has the impact on viewers that is suggested by the Patton quotation above. That is, can watching this film promote the building of more accurate conceptual understandings about the proportions of the universe? This classic film has been used in science classes at a variety of levels and is an essential teaching tool in many physics classes. Given the widespread use of this film, the dearth of research on its effectiveness is surprising. Coinciding with the lack of research on the film's instructional efficacy is an equally scant research base on how scale and scaling is learned and applied.

An understanding of scale is becoming increasingly important due in part to technological advancements that now allow us to explore "new worlds" that reside within the smallest (nanoscale) and the largest (cosmic) realms of science. New forms of microscopes and new techniques for working at the nanoscale are having significant impacts on directions

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and advancements in engineering and manufacturing. Nanoscale science is leading to new products in textiles, electronics, materials science, and bioengineering. Without an understanding of just how small nanometer sized materials are, it is unlikely that students could make informed decisions about the use of nanotechnology and nanoscale hazardous materials. Considering the largest end of the scale, one might question students' ability to understand how scientists know if black holes exist or whether or not we would want to send an astronaut to the edges of our solar system without a sound appreciation for scale. The need to understand how students learn about scale has emerged as a significant challenge for education researchers. For example, there is a current debate amongst those engaged in nanoscale education regarding the teaching of nanotechnology to elementary students. Little is known about when an understanding of scale is developmentally appropriate and even less is known about the prerequisite skills that are needed for a meaningful understanding of scale and scaling applications.

Purpose and Significance of the Study

This study takes an important first step in the exploration of how middle school students learn about scale through the classic film ''Powers of Ten.'' Although the medium of film is not new, the challenge of representing complex science phenomena has perhaps never been greater. Technological advancements in educational media now allow instructional designers to create a wide range of virtual representations that involve complex three-dimensional graphics, haptics, auditory enhancements, and virtual reality (c.f. Barab *et al.*, 2000; Fabos and Michelle, 1999; Yang *et al.*, 2003). New forms of interactivity engage the learner in ways that until recently we have only been able to imagine. Even with this array of new instructional technologies, there is relatively little research that directly investigates the influence representations of science phenomena with electronic media on student learning. The film ''Powers of Ten'' has remained as a landmark instructional tool that continues to be viewed as innovative in its approach to teaching students about the variation that exists in the natural world from cosmic to atomic scales.

Scale has been identified as one of the central themes that cuts across the science domains (American Association for the Advancement of Science, 1993). Whether the topic is in biology, chemistry, physics, earth or space science, issues of scale are central to understanding science phenomena. New tools have made previously inaccessible areas of science accessible. New forms of telescopes such as infrared, radio, and x-ray telescopes allow us to explore the new areas of the universe, and as a result opening new areas of study. At the opposite end of the scale, new tools such as the atomic force microscope allow for the exploration and manipulation of materials at the tiniest of scales. These advancements place new demands on educators to produce students who can flexibly move from one scale to another with conceptual ease and accuracy. Students must now be able to visualize and mentally maneuver among and within universal, galactic, stellar, planetary, macro (human), micro, and nano scales. Thus the significance of this exploratory study lies in its potential to highlight the strengths and weaknesses of a commonly used tool in the teaching of scale and its ability to add to the limited knowledge base regarding students' conceptions of this complex topic.

Students' Understandings of Scale

Our previous studies have suggested that students have great difficulty conceptualizing scales that exist outside of the typical human experiential range (Tretter *et al.*, 2006). This is evidenced by their reliance on familiar objects as cognitive referents. Very young students think about scale with broad conceptual benchmarks thinking of *large* with units such as the length of a school bus. Middle school students move from thinking about *large* as school bus lengths to thinking of larger units such as a track on an athletic field. High school students are able to think in even larger units such as the size of a shopping mall. At the other end of the scale, to young children an ant is sometimes the smallest thing they can conceptualize, whereas middle and high school students conceptualize *small* as microscopic objects such as a blood cell.

These previous studies also showed that students of all ages have more trouble understanding very small scales than they do large scales. Moving down in size from a millimeter, most students just think of things as *small* and have difficulty differentiating something nanometer-sized from something micrometer-sized; there is a point where small is just *undifferentiated small* to students. It is suspected that one of the reasons that students are able to move more flexibly into the large scales is the due to the wealth of opportunities they have to experience these large scales. Perhaps, students are able to use visual clues to conceptualize long distances, clues that are not as readily available for small distances. Telescopes, binoculars, and zoom cameras provide visual information about objects at large distances and experiences such as flying in an airplane or traveling long distances by car provide students with opportunities to shift their perspectives and consider larger scales of distances. Visual clues are lost when students move beyond the microscale where small objects are represented by arrays of data and are not visible. Students often hold naïve concepts about the relative sizes of small things, such as believing a virus is significantly larger than a bacterium (Jones and Rua, in press). Experts report that rather than moving through a continuum from one scale to another, instead they *jump to different worlds* when they are working at very large or very small scales (Tretter *et al.*, 2006). Pozo and Crespo (2005) noted a similar phenomena in students' concepts of matter. They found that students of a wide range of ages view matter as discrete and had difficulty conceptualizing the continuous nature of matter.

A recent study by Hegarty *et al.* (2006) outlines important differences between the abilities to visualize and problem-solve with smaller-scale (i.e., "desktop-scale") objects or images that can be represented in books or computer screens and larger, environmental-scale spaces such as a building interior or town. In this study, the researchers looked at the ability to answer questions about an environment which they walked in, watched a video of, or experienced in a desktop virtual reality system. In addition, they looked at correlations of performance on these tasks and on tests of small and large scale visualization. An important outcome was that performance on tasks discerning spatial configurations in large-scale environmental spaces was highly correlated with their ability on tests of small-scale visualization. However, this was particularly true when all that was available was visual information (e.g., video or virtual reality). When individuals physically walked the environment, performance began to diverge. Similarly, when the large-scale environmental task was related to route representation (sequence of locations and the direction and distance between them), these abilities were not correlated with small-scale spatial configuration ability.

These findings by Hegarty dovetail with other work in cognition and perception that point to differences in how individuals perceive spaces and objects of different scale. Previc (1998), in a summary of neuropsychology research, concluded that distinct cortical networks of the brain were responsible for visual tasks with smaller objects near the body and navigating large-scale environmental spaces. Research by Bryant and Tversky (1999) demonstrated that the task and the qualities of the visual stimuli will induce individuals to make use of a mental framework that are either "exterior" or "interior" to the space. That is, the frame of reference can be from the outside of the space being visualized looking in or referenced as though you are surrounded by the objects. The framework taken can be influenced both by what is represented in the image and the degree to which rich depth cues are available. This work builds directly off of earlier theories developed by Ittelson and others (Elliot, 1987; Ittelson, 1973) which noted the distinctive differences between visualizing environmental and small-scale spaces.

Just as Hegarty's work points to differences in how different mental processes are used to visualize geometric configurations of objects and topological route-making through space, another body of research points to the differences as to how visual imagery and verbal/textual information is processed differently by the brain. Hegerty's study found that there was no correlation between a test of verbal ability and performance on any three of the large-scale space stimuli they worked with. This is in line with research by Paivio and colleagues (e.g., Paivio, 1983; Clark and Paivio, 1991) which indicated the distinction of mental processes involved in visual imagery and verbal information processing. Cognitive processes make use of these symbiotic but functionally independent systems; with visual information being processed in a parallel manner while verbal information is more serial in nature. Also, concrete objects lend themselves more to visual imagery while abstract concepts are often more easily managed with the verbal system. Scale, in fact, has both concrete and abstract components. While the "Powers of Ten" film is largely visual in nature, it verbally references the objects/spaces being displayed and notates the scales in a text/numeric format. Also, most all of the scales are of objects that cannot be directly perceived by humans and, therefore, have to be represented through abstraction to some degree.

It seems that for many students an understanding of scale begins with understanding relative scale, as they learn which objects are larger than other objects. Young children have a natural fascination with very large things such as dinosaurs and whales.

Chi and Koeske (1983) have shown that children's detailed knowledge of dinosaurs represents an expert knowledge where children can flexibly compare traits and characteristics of a wide range of dinosaurs. At small scales, children are also fascinated by the unseen worlds that microscopes reveal. In a study of elementary, middle, and high school students, we found that students are more accurate in their understanding of sizes of objects relative to one another than they are of mathematical scale (Tretter *et al.*, 2006). Taking children from comparisons of objects they can visualize to abstract, mathematical concepts crosses into another set of abilities. Understanding mathematical scale also requires that students be knowledgeable of exponential notation. As Confrey (1991) showed in a study of students' concepts of powers of ten, understanding exponential notation is difficult for students and may result in concepts that are a hybrid between logarithmic and linear scales. According to Confrey, the challenge for students in understanding scientific notation is to create transformations of logarithmic scales into a meaningful and functional number line. The conceptual sites of place values are difficult because the powers of ten are multiplicatively increasing. Nonetheless, students must master a conceptual understanding if they are to move beyond a surface level conceptualization of scale.

Moving from one scale to another requires an understanding of proportional reasoning. Research on proportional reasoning has shown that "(d)espite its importance in everyday situations, in the sciences, and in the educational system, the concept of proportions is difficult" (Tourniare and Pulos, 1985). Proportional reasoning emerges in middle school and has been described as being a cornerstone to higher mathematics (Lamon 1994; Lesh *et al.*, 1988). To be able to move flexibly from one power of ten to another with meaning requires that the individual be able to apply proportional reasoning.

The Powers of Ten

The "Powers of Ten" film (http://powersof10.com) begins with a an aerial view of two people on a picnic blanket with a view one meter wide and taken one meter above the earth. The film moves every ten seconds out by a factor of ten, showing the view at 100 meters, 1,000 meters, out into distant space. Then the process reverses, zooming back into the original view of the two people on the blanket. At that point the film zooms inside the skin moving in factors of ten, showing increasingly smaller views. A number of complex concepts are presented in visually interesting ways including ideas of zooming in and out, as well as how things look different at different scales. Students can see the people at different distances as the view moves into space away from earth, as well as how things look as the perspective moves inside the skin of the person on the blanket showing images of a lymphocyte, then the coiled strands of DNA, on to the innermost electrons of a carbon atom.

The film brings together both verbal and visual representations of scale. The visual images show both imagery representing the different scales and blocks of text on either side indicating the scale both with and without exponential notation. These visual images are reinforced with a narrative track that expands on what is being seen in the images. Whether shown on a computer screen or a wall-mounted projection screen, the film provides a pictorial representation of objects and space rather than an experience where individuals can use visual depth or sensorimotor cues available when you move through a space. Since it is film, these images are shown in sequence. However, the stroboscopic effect of many image frames per second, small changes between frames and a reference square expanding or contracting on the screen provides a sense of continuity between the different scales. While the scales from 10^{-1} to 10^{7} can be represented with traditional visible light photography, larger and smaller scales used more abstract representational means to generate imagery. An even smaller range, 10^{-1}–10^{4}, is probably within the range of most participants' experience with the unaided eye.

The first draft of the film was made in 1968 although the version most commonly used was made in 1977. Undoubtedly the most famous of the Eames films, "Powers of Ten" is probably one of the most seen short films of the post-war era and continues to be shown today by science teachers at both precollege and college levels. In a separate study that examines how experts learn scale (Jones *et al.*, 2006), people from a variety of professions cited the "Powers of Ten" as one of the ways they learned about scale. A neurosurgeon reported when asked during an interview, "what experiences did you have in school learning about scale?" replied, "I remember seeing in one of my science classes in high school or middle school that movie that starts with, you out in the middle of the universe and there are squares that come in. I remember of seeing the film and it ends up with some guy in Grant Park, It goes from massive distances out in the universe to through the Earth's atmosphere down into; I remember seeing that movie in school. I went to a private school that went from six grade to high school... Somewhere during that experience at school I remember seeing that movie. I was pretty fascinated by it. I remember that movie vividly, down to the point, it has probably been 25 years since I have seen it, and I still remember the guy's hand in Grant Park.''

What makes this video so memorable and does it promote conceptual understandings of scale? Do students develop understandings of both large and small scales or are understandings of scale after watching this film skewed toward large scales as our previous work would suggest? This exploratory study sought to understand these questions.

METHODOLOGY

Research Questions

The following questions guided the design of this study:

- Does viewing the film, ''Powers of Ten'' alter students' understandings of spatial distances over many orders of magnitude?
- If there are gains in knowledge, are there differences in students' understandings of large and small scales?

Participants

There were two types of participants in the study: middle school students and experienced teachers. The student participants for this study consisted of twenty-two girls (16 Caucasian, 4 African-American, and 2 Asian) who attended a two-day summer program about cell biology at a large university in eastern United States. The program was designed to provide enriched summer science experiences that would encourage girls to continue to pursue interests and careers in science. The grade level of the girls ranged from 7th grade through 9th grade with an age range of 11–14 years old. Study participants attended a variety of public and private schools throughout the urban community. Most of the participants attended the camp out of interest in mathematics and science and as a consequence may not have been representative of typical of middle school students.

Prior to this camp, nine participants attended another week of camp that also included mathematics and these participants completed the *Proportional Reasoning Assessment Instrument* (Allain, 2001). The participants completed a three-part assessment that included pre- and post-interviews and a card-sorting task (described further below). The interviews were individually conducted by a team of researchers comprised of one male and three females.

Additionally, a sample of science educators ($n = 6$) who had extensive experience using the ''Powers of Ten'' film with students completed a short written survey regarding their interpretation of the educational value of the film. Each of the educators had shown the film at least 10 times to different classes. Four of the educators had taught high school physics, one was a science teacher educator, and one was a university biology instructor.

Assessments

Prior to watching the film, student participants were interviewed about their knowledge of the film ''Powers of Ten'' as well as their previous experience with the mathematical concept of powers of ten. The semi-structured interview (see Appendix A) also asked students about their perceptions of the sizes of a range of objects and distances. This pre-interview included questions concerning scientific notation and units. Responses were recorded by hand by the researcher.

After the pre-interview, each student completed the *Scale Card Sort* (SCS) task which was adapted from that used by Tretter *et al*. (2006). It is designed to assess students' understandings of relative sizes and distances. Each student received twelve cards on which was written the name of an object or distance and a diagram or photograph. Students were asked to order the cards from smallest to largest (see Appendix B). The students also received scientific notation labels with instructions to match the label to the corresponding object card and attach the label with tape. After completing the card-sorting task, participants watched the 21-minute video ''Powers of Ten.''

At the conclusion of the video, each student was again individually interviewed. This post-interview asked the participants to describe aspects of the video that were particularly interesting to them. Participants were also asked to identify parts of the film that they already knew, as well as what they felt they learned from the video regarding size and distance. The interview also assessed participants' perceptions of the difficulties of understanding small and large scales.

After this post interview, participants completed the *SCS* task again, this time participants were asked to reason aloud as to why they were lining the cards up in a particular order as well as why each label was attached to the cards. The interviewer probed responses with further questions as each sorted and labeled the cards.

A subsample of student participants was part of another study of mathematics reasoning and these nine participants completed a proportional reasoning test two weeks prior to the onset of this study. The *Proportional Reasoning Assessment Instrument* (Allain, 2001) includes ten open-ended items featuring missing value, comparison, mixture, associated sets, part-part-whole, graphing and scale problems.

The experienced science teachers were asked to complete a written survey of their perceptions of the film "Powers of Ten" as a teaching tool. The survey included five questions that asked them how many times they had shown the film, their beliefs about what the film teaches, the technical features of the film that make it effective or not, the main focus of the film, and other comments.

Analyses

Student participants' interview responses were entered into a matrix and students' responses were compared pre and post to the viewing of the film. The pre and post cart sorts were analyzed to determine the number of cards that each participant placed in the correct sequence from small to large. Each card was compared to every other card and if the order was correct then a code of 1 was assigned for the placement. If the order was incorrect the card was assigned a 0. The number of concordant pairs was compared pre to post with a t-test to see if there were significant changes as a result of viewing the film. The scientific notation assigned to each card was analyzed by determining the frequency of correct responses. Proportional reasoning scores were correlated with card sort ranking scores to explore whether or not there was a relationship between scale ability and proportional reasoning.

The science teacher surveys were analyzed for commonalities across participant responses. Responses for each survey item were examined and entered into a frequency matrix.

RESULTS

Pre-Instruction Interviews

The pre-interviews showed that 45% of the student participants had heard of the term "powers of ten," 36% of the students recalled learning about the topic in mathematics, and 28% remembered studying it in science classes. Seventy-seven percent of the participants recalled learning about the sizes of things in school. Most of the students remembered studying metric scale, distances, volume, and area. Other students stated that they learned about sizes of things when studying geometric shapes, as well as map scales. Twenty-three percent of the participants specifically noted that they learned about the sizes of things when they compared the sizes of different objects.

Participants were also asked to state the largest size or distance they could think of and the responses ranged from specific objects or measurements of distances (e.g., the universe, Pluto's orbit) to linear measurements (e.g., one kilometer, a light year). Twenty-seven percent of the girls said that a mile was the largest distance they could imagine and eighteen percent said that they thought of a kilometer. Other largest distance responses were the equator, infinity, and the Empire State Building. However, students sometimes thought of relatively small sizes (when asked to name the largest distance) as indicated in these responses, "around the track," "three football fields," and "a big TV." One thoughtful student asked, "is there even an end to distance?" When asked to state the smallest size or distance they could think of, 50% of the students said a millimeter. Other typical responses included "the width of paper," "DNA," "virus," and "termite."

During the pre-interview, participants were asked if they had ever heard of scientific notation. All of the students responded positively. Seventy-seven percent said that they used scientific notation in math class and 45% said they had also used it in science class. The participants were also asked to respond to the question "what is a kilometer?" Fifty percent said that they knew the prefix kilo- means 1,000. Twenty-three percent stated that they did not know what a kilometer was. The other responses indicated a lack of accurate knowledge such as, "smaller than a meter."

On the other end of the size continuum, participants were asked to respond to the question "what is a millimeter?" Only eighteen percent of participants stated that it is a 1,000th of a meter. The rest of the responses were less accurate such as, "bigger than a piece of paper" and or "the smallest measurement."

Participants were asked to describe how the numbers 243 and .01 would appear in scientific notation. Correct responses to the number 243 were given by 82% of the participants and 77% correctly responded for the number .01.

Post-Instruction Interviews

Participants were asked what they had learned from the film that was new about size and distance and the most frequent responses were powers of ten (18%), the size of atomic parts (14%), and microns (9%). To assess the overall perception of the film participants were asked to describe what the film was about and 41% said "powers of ten." Thirty-six percent said the film was about "size and measurements" and 27% said it was about "viewing the distances of things."

Large Versus Small Scale

During the interview participants were asked, which is harder to understand small or large scale and why. Sixty-four percent stated that small scale was more difficult. Reasons that small scale was considered difficult included the difficulty students have in seeing microscopic things, using negative numbers in exponential notation, and the names given to the measurements. Nine percent stated that large scale was more difficult and fourteen percent said that both large and small were difficult. One participant who noted that both scales were difficult also stated that it depends on your perspective when observing something. Although the film emphasizes the emptiness of space at the extreme ends of large and small scale, none of the students commented on this as a major emphasis of the film.

Powers of Ten

Student participants were asked, "What does powers of ten mean?" Fifty percent of the responses included discussing the use of the number 10 in exponents as well as giving an example, such as "Ten to the negative seven." Often, an example of powers of ten was given when lack of an exact meaning could not be voiced. Twenty-seven percent of the participants said that a power of ten means "times ten to everything" and one said it is a "way of writing large numbers." Even after viewing the film, eighteen percent of the participants admitted that they did not know what powers of ten meant. After viewing the film, the participants were asked if they remembered studying powers of ten in school. Sixty-eight percent said yes (compared to only 36% during pre-interview) and twenty-seven percent said no (compared to 46% during pre-interview).

Affective Responses

When asked what aspects of the film were most interesting, student participants' responses diverged according to scale. Fifty percent enjoyed the scenes describing the very microscopic things as the scenes in the film went under the skin and fifty-five percent found the zooming out into the universe interesting. Both large and small scale were considered interesting to students. Students were most interested in the aspects of the film that featured ends of the scale continuum that are not visible with the naked eye.

Scale Card Sort Activity and Proportional Reasoning

The *t*-test of the pre and post card sort showed that there were significant differences in the accuracy of students' sorting by size $t(22) = 3.79$, $p = 0.001$. Students' mean pretest score for accurate card positioning was 60.09 and posttest the mean was 62.59.

The pre and post cart sort tasks were also analyzed to determine if students could match the correct scientific notation to the card based on size. The frequencies of correct responses for card powers of ten labels for the pre- and post-sorting tasks were calculated. Table 1 lists the scientific notation labels and the mean frequencies of card labels attached correctly during the pre and post card sorting task. The card sort scores were positively correlated with participants' proportional reasoning scores ($r^2 = .89$, $p = 0.001$).

The mean frequency of correctly labeled items increased from pre to post for all the cards except for two. The card indicating the diameter of DNA (10^{-7}) had no change from pre to post. The card indicating the distance from Earth to the International Space Station (ISS) (10^5) had a small decrease in correct responses from 32% to 27%, possibly due to participants' lack of familiarity with the ISS as well as the fact that is was not mentioned in the "Powers of Ten" video. The mean increase in the percentage of cards with correct labels was 20%. The largest mean increase (54%) was seen for the scientific notation label 10^{-15} which corresponded to the diameter of a proton. The proton size was specifically mentioned in the film.

Table 1. Means and Standard Deviations for Correct Scientific Notation Metric Card Labels (Pre and Post)

Card Label (metric)	10^{-15} Diameter of proton	10^{-9} virus	10^{-7} Diameter of DNA	10^{-5} Diameter human hair	10^{-3} Thickness of dime	10^{-1} Width adult's hand	10^{0} Height 5 yr old girl	10^{1} Width football field	10^{3} Distance 10 min walk	10^{5} Distance Earth to ISS	10^{7} Diameter of Earth	10^{11} Distance Earth to Sun
Pre Mean (SD)	0.23(0.43)	0.18(0.39)	0.32(0.48)	0.64(0.49)	0.55(0.51)	0.50(0.51)	0.55(0.51)	.46(.51)	0.41(0.50)	0.36(0.49)	0.32(0.48)	0.86(0.35)
Post Mean (SD)	0.77(0.43)	0.27(0.46)	0.32(0.48)	0.82(0.39)	0.77(0.43)	0.73(0.46)	0.77(0.43)	.73(.46)	0.73(0.46)	0.27(0.46)	0.36(0.49)	1.00(0.00)

Experienced Teacher Perceptions

The results of the survey of the experienced teachers showed that all of these educators found the film to be a highly effective instructional tool. The reasons given for the film's effectiveness included: "the ability of the film to relate the different levels in the powers of ten to real-life images that allows the students to compare and contrast," "stimulating cognitive interest and perception beyond the human scale," "causes the students to think of questions," and "it is easy to understand in everyday terms." The experienced teachers noted that the design of the film that allowed students to move slowly from the human scale to the large (and small) scales and then quickly back again was effective in laying the foundation for understanding the different scales. Another teacher noted that this is the first time that many students are introduced to the idea that there are boundaries to the known universe.

Each of the teachers was asked to briefly explain what the film was about and all of the teachers noted it was about spatial scales and human perspectives within the ranges of scales. Three of the teachers noted the film teaches about the vastness of inner and outer space. The film makes a point when the scale reaches the largest scale and again when it reaches the smallest scales that there is mainly empty space.

DISCUSSION

This study showed that even though the film is a relatively short-term instructional intervention it significantly influenced students' understandings of powers of ten scale. Students entered the study with some knowledge of exponential notation and most could write numbers in exponential notation. As suspected, knowledge of large and small scale tended to be more limited to students' direct experiences. Moreover, knowledge of specific measures of metric scale beyond a meter was uncommon. Students had difficulty with sizes that were outside of the human scale and after viewing the film students reported that they were most interested in the aspects of the film that focused on scales that they could not experience directly. Students reported that they learned the most about the scale of atoms, cells, galaxies and the mathematical notation of powers of ten. Small scale was considered by participants to be more difficult to conceptualize than large scale due to the reported difficulties they had in visualizing things at this scale. The data showed that students' concepts of relative size were significantly more accurate after viewing the film. Participants' ability to accurately match metric sizes in scientific notation increased from pre- to post-viewing of the film.

It is interesting to note how the examples of small and large objects given by the students ranged between objects or spaces which they directly experienced, and objects and spaces which they had seen in more abstracted forms as images in books or on TV. It is not within the scope of this study to differentiate the impact of the direct experience and indirect representations. However, the bias towards more easily conceptualizing about larger scales may be because students found it easier to ''scale down'' large scales to environmental spaces in which they could move through using an interior viewpoint mental framework. This would allow them to link these large scales to past experiences moving around/through physical objects and spaces. With very small scales, in absolute terms, you have to pass down through environmental scale spaces, then through desktop-scale, to smaller scales. When visualizing such small scales, do children choose to expand them to desktop-scale representations where they take an exterior view of the object, or expand them further to environment-scale spaces where they can take an interior viewpoint? Perhaps the quandary of the appropriate scale needed to visualize (and thus conceptualize) such small-scale spaces leads to the differential in students' comfort level in conceptualizing the very large and very small.

Previously we reported that elementary, middle and high school students find relative scale easier to conceptualize than absolute scale (Tretter *et al.*, 2006). This was particularly true for younger students. When students have had prior experiences with objects and distances, their relative and absolute understandings are more accurate than when they have had limited experiences such as those for large and small scale. The younger the student, the larger the disparity between the accuracy of relative and absolute scale concepts. Furthermore, younger students had a more difficult time conceptualizing very small scales than larger scales.

Understanding of relative scale comes with age and/or direct experience with objects of different sizes. To deal with the myriad of information bombarding us on a daily basis, one may learn to organize it all by categorizing/lumping the knowledge into existing schema. Children may acquire more slowly internal representations of merely typical but not functionally critical sizes of things (Sera *et al.*, 1988). As children acquire more experience, the idea of absolute size and relative size may become a little less confusing. Students can grasp the idea of big and small relative to other things, but explaining the absolute sizes of things is much more complicated. When the participants in this study were asked to give examples of small and large objects, most the participants stated things that they either had direct experience with or had seen on TV, movies, etc. The ability to discuss small and large depends on participants' linguistic ability to verbalize about relative scale. Everyday spatial language is not very precise, for example expressions like ''next to'' or ''between'' are common (Tretter *et al.*, 2006). The students were more comfortable talking about things that they can see or possibly have had experience with, but are more interested in things they cannot see (at the very small and very large scales). As students' familiarity with very large and very small numbers, ratios, and powers of ten improves, extremes of scale may become more meaningful (AAAS, 1993). The video ''Powers of Ten'' allows one to see scale differences beginning with the familiar to the large scale and then back through familiar down to small scale while incorporating the corresponding scientific notations. Moving along a continuum through the distances, the video allows for the direct comparison of relative sizes by sandwiching the familiar scale in between the large and small scale.

Scale concepts are further complicated by schema construction that can consist of both imagery and verbal information. Connections between these elements may be linked (or not linked) in such a way as to represent a series of discrete elements or relatively undifferentiated networked elements. An important question to ask is how were the schemas of these participants organized? The influence of the ''Powers of Ten'' film on their performance on the scale assessments and the differential ability to work with relative and absolute scale points to how this scale and scaling schema might be organized. The ''Powers of Ten'' film design seems to be most successful at creating an organizational sequence of declarative elements. In the film, the elements named in the narration and reinforced as a graphic image seemed to be remembered as a temporal position in the film relative to other objects (e.g., protons showed up at the end of the film). It is important to note that sorting of objects named in the film (the proton) improved on the post-test, while those that weren't (the ISS) did not. The influence of the film on the ability to successfully attach a mathematical scale to an element is less clear. The link of mathematical scale to an object is done in the film by temporally and spatially showing the text of the scale adjacent to the visual image. As noted, children's ability to recite the absolute scale of an object, as opposed to know its scale relative to other objects, develops later. Improved performance on the card sort task may be because the film was successful in linking a scalar value to an image and name in memory or, again, it may be that the ordinal linking of elements allowed participants to order the objects and then attach to correct given mathematical scales, in order, to the images.

The positive correlation between accuracy of scale as seen in the card sort task and the proportional reasoning task suggests that further studies are needed to see if this result persists in larger studies. Understanding the sizes of things and the mental maneuvering required to move from one scale to another requires the ability to apply proportional reasoning. These results suggest that if a student is not proficient at proportional reasoning they may not be highly accurate in understanding the differences in object sizes and distances. The implications of this finding may be significant. If proportional reasoning is necessary for students to meaningfully learn about scale and scaling then it may be of little value to try to teach elementary students scale beyond that which they can experience concretely. Students consistently mentioned prior experiences as reasons for their responses and laying a solid foundation of experiences in early grades with measurement and estimation tasks may prove essential for more complex understandings.

Teachers noted that the film focused on the vastness and emptiness of space at the largest and smallest of scales. This feature of the film was not noted by any of the students but was reported by half of the educators surveyed. This concept can be problematic for students to conceptualize. Pozo and Crespo (2005) reported that the discontinuous nature of matter and the idea of empty space at the smallest of scales is in opposition to our implicit theories of nature and to change this cognitive representation would require significant cognitive change. Pozo and Crespo found that the majority of students from 12 to 17 years of age had difficulty conceptualizing empty space between particles of matter. Further research is needed to explain and predict how and when individuals develop more sophisticated understandings of matter at the smallest (and largest) scales.

One key question remains unanswered, "What makes this film a useful learning tool?" This initial study was able to document that learning occurred and what students reported as the essential focus of the film but the data cannot explain which specific aspects of the film were effective. Perhaps it is due to the zooming in and out, which provided students with two (repeated) opportunities to view the various objects (at each of the powers of ten). Maybe the zooming created a sensation of continuous movement even though the perspective of the viewer changed from up to down on the object being viewed.

As a learning tool, it will be important to explore the impact of both physical and pictorial representations of objects. As noted in the literature, different cognitive processes are used to visualize and problem-solve with desktop-scale objects and larger scale environmental spaces. What is the efficacy of building a room-size model of a cell, or laying out a small-scale model of the solar system in the school gym as opposed to watching pictorial images in the Powers of Ten film? How might they work together to reinforce the concept of scale?

Limitations

The results of this study should be interpreted with care until these exploratory results can be verified by other researchers with other populations of participants. All of the participants were females and different results may be obtained if both males and female students were involved in the study. It is also highly likely that different results would be obtained if the study were conducted with students who were raised in a culture that strictly used the metric system.

Implications

The results of this study suggest that teachers may need to explicitly teach students about both relative and mathematical (absolute) scale. Students are likely to encounter difficulty with those aspects of scale that are beyond normal human experience. However, the affective results suggest that students are highly interested in learning about very large and very small scales. The film appeared to be a successful tool in improving participants' understandings of scale but additional instruction would be needed to promote a more comprehensive understanding of scale and the powers of ten. Further research is needed to determine if an interactive version of the "Powers of Ten" would be more effective in teaching scale. This type of media could allow students to control the pace of the instructional program and allow them to move forward and backward as they compared and contrasted different scales and examples.

APPENDIX A: INTERVIEW QUESTIONS

A. Pre-Instruction Interview Questions

1. Have you ever heard of scientific notation? (When, where?)
2. Have you ever heard of powers of ten? (When, Where?)
3. Have you studied the sizes of things in school?
4. Have you studied the powers of ten in school?
5. What is the largest size or distance you can think of? (Can you give an example of something that size or distance?)
6. What is the smallest thing or distance you can think of? Can you give an example of something that size or distance?

B. Post-Instruction Interview Questions

1. Were there aspects of the video that were of interest to you? If yes, what?
2. What did you already know about size and distance that was shown in the video?
3. What did you learn new about size and distance?
4. If you were to describe in a few words what this film was about—what would you say?
5. Do you think large or small scale is more difficult to understand? Why?
6. What does powers of ten mean?
7. Have you studied sizes of things in school?
8. Have you studied the powers of ten in school?

APPENDIX B: CARDS IN THE CARD SORT TASK

10^{-15} Diameter of proton
10^{-9} Typical virus
10^{-7} Diameter of DNA
10^{-5} Diameter of human hair
10^{-3} Thickness of dime
10^{-1} Width adult's hand
10^{0} Height 5 yr old girl
10^{1} Width of football field
10^{3} Distance you could walk in 10 min
10^{5} Distance Earth to ISS
10^{7} Diameter of Earth
10^{11} Distance Earth to Sun

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