Computers & Education 72 (2014) 367–377

Contents lists available at ScienceDirect

Computers & Education

journal homepage: www.elsevier.com/locate/compedu

Learning strategies and multimedia techniques for scaffolding size and scale cognition

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A R T I C L E I N F O

Article history:
Received 9 October 2013
Received in revised form
22 November 2013
Accepted 27 November 2013

Keywords:
Size and scale
Multimedia learning
Assessment
Online learning

A B S T R A C T

Size and scale cognition is a critical aptitude associated with reasoning with concepts and systems in science, technology, engineering, and mathematics (STEM). However, the teaching and learning of concepts related to size and scale present major challenges because objects at certain scales are unable to be perceived by humans with the naked eye. A potential way to overcome this challenge could be by means of learning strategies coupled with multimedia learning. In this study we propose learning strategies, instantiated by multimedia are for learning tools that may result in improved learning of size and scale cognition based on the FS2C framework. This framework consists of five levels to characterize size and scale cognition and the cognitive processes supporting them. Participants of this quasi-experimental design included 224 undergraduate students who experienced one of three different multimedia for learning tools, and then were assessed through five tasks whose design was based on the FS2C framework. Results suggest that learning strategies prompting students to compare objects of different sizes, may increase their abilities in ordering and classifying objects. Having students to interact with a logarithmic scale may also have increased participant posttest performance scores in the numerical proportional and absolute measurement tasks. Finally, we propose that the use of multimedia for learning affordances like 3D interaction, zoom in and zoom out, and direct interaction with a scale metaphor may help students make explicit connections and become familiar with objects of different sizes and scales.

1. Introduction

Size and scale cognition is a critical aptitude associated with reasoning with concepts, models and systems in science, technology, engineering, and mathematics (STEM) that has become imperative for students hoping to possess a comprehensive understanding and working knowledge of STEM. However, the teaching and learning of concepts related to size and scale present major challenges because some scales (e.g., micro, astronomical, nano) are unable to be perceived by humans with the naked eye. Therefore teaching and learning about size and scale represents a problem that has been described as "conceptual and practical; objects and concepts at the nanoscale are hard to visualize, difficult to describe, [and] abstract, and their relationships to the observable world can be counterintuitive (Sabelli et al., 2005)." A potential way to overcome this challenge could be by means of multimedia learning, which refers to the process of construction of knowledge by creating mental models from words printed or spoken in combination with pictures that could be either static or dynamic (Mayer, 2005a, pp. 1–16). According to Mayer's Cognitive Theory of Multimedia Learning, students are found to learn more deeply from words and pictures than from words or pictures alone (Mayer, 2001). Based on these principles, we believe that multimedia learning provides new possibilities, meaning their affordances, to teach and to learn about size and scale. Affordances can be described as the perceived and actual functional properties of a thing that define how such thing could potentially be used (Gibson, 1979). Interactive multimedia learning may offer affordances for teaching and learning that may provide instant feedback, a multimodal and multiscale presentation of information, intelligent guidance to facilitate sense making, and access anytime and anywhere (Magana, Brophy, & Bryan, 2012).

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0360-1315/$ – see front matter
http://dx.doi.org/10.1016/j.compedu.2013.11.012

In this study we investigate what are learning strategies that can be coupled with multimedia for learning tools that may result in improved learning of size and scale cognition. To this end we will use the FS2C framework proposed by Magana, Newby, and Brophy (2012) which was informed by developmental psychology literature and recent findings in nanoscale science and engineering education. This framework was employed in two different ways (1) to inform the design or selection of a multimedia for learning tool aiming to convey the proposed forms of size and scale cognition as prescribed by the FS2C framework, and (2) to investigate the effectiveness of this tool in increasing participant performances in the FS2C-designed tasks. A major goal of the study was also to identify the efficacy of three different learning strategies and the corresponding affordances of multimedia techniques or scaffolds that might have led to improved learning. The research questions for this study are this:

What are learning strategies that can lead to the biggest effect (if any) on students' learning about conceptions of size and scale according to the FS2C framework?

What are the potential affordances of multimedia for learning tools that can lead to the biggest effect (if any) on students' learning about conceptions of size and scale according to the FS2C framework?

2. Background

2.1. Size and scale cognition

Advances in science and engineering have resulted in the development of new tools, techniques, and instrumentation that allow the study of phenomena at different and multiple scales and the design and implementation of new solutions in health care, energy, economic competitiveness, and national security. For instance, multiscale modeling approaches are being used in such disciplines as engineering, materials science, mathematics, physics, chemistry, biology, meteorology, computer science, and so on, to understand complex physical problems with important features at multiple scales (Horstemeyer, 2010). Understanding these problems may also require a strong spatial ability involving reasoning proportionally when using scale models. It is therefore impetrative for young learners to possess size and scale cognition starting from young ages, such as when in middle school, and continue to develop these capabilities until achieving a comprehensive understanding and working knowledge.

Learning objectives associated with concepts of size and scale have been identified as relevant in different education benchmarks and standards at the national level. For instance, the American Association for the Advancement of Science (AAAS, 2006) learned that students in grades 6 through 8 should become familiar with ratios, very large and very small numbers,, and work with powers of ten. The benchmarks also emphasize that "understanding the notion that things necessarily work differently on different scales is more difficult than recognizing extremes, hence students should study a variety of different examples" (AAAS, 2006). Students typically begin using powers of ten in high school and therefore can make it easier to describe great differences of scale, but not necessarily to make them comprehensible. Furthermore, the recent framework for K-12 science next-generation standards emphasizes reasoning abstractly and quantitatively (BSE, 2011), both being cognitive processes associated with reasoning about size and scale, which also represent underlying concepts associated with the use of mathematical models and computational thinking.

However, research findings conducted with middle-school students indicate that these learners do not demonstrate an adequate understanding of concepts of scale and size, especially at the micro and nano levels (Tretter, Jones, Andre, Negishi, & Minogue, 2006). These findings are further corroborated by results from the National Science Report Card. For instance, according to the science section of the National Assessment of Educational Progress (NAEP, 2005), only at the *proficient level* do students at the end of their middle school have an emerging understanding of the particulate nature of matter, and at the advanced level they have a modest understanding of scale (NAEP, 2005). NAEP's assessment conducted in 2005, found that 59% of eighth-grade students scored at or above the basic level, and 29% performed at or above the proficient level of achievement. In the 2009 assessment, 63% of eighth-graders performed at or above the basic level, 30% performed at or above the proficient level, and 2% performed at the advanced level. Also, in the 2011 assessment, 65% of eighth graders performed at or above the basic level, 32% of eighth graders performed at or above the proficient level and 2% at the advanced level. Although increases have been achieved by students performing at a proficient level, none has been found in students performing at the advanced level, where students start to demonstrate a modest understanding of scale.

2.2. The FS2C framework

Developing instructional methods and assessments to evaluate and scaffold students' learning of phenomena at different scales and the behavior of phenomena at such scales require a working framework. The FS2C framework provides a vehicle for defining different forms of size and scale cognition and articulating their critical factors and their relationships necessary for describing them (Magana, Brophy, et al., 2012). The development of the FS2C framework was informed by developmental psychology literature and recent findings in nanoscale science and engineering education. Table 1 summarizes the components of the FS2C framework for characterizing and scaffolding

Table 1
A Framework for characterizing and scaffolding size and scale cognition (FS2C) and the cognitive processes supporting them (from Magana, Brophy, et al., 2012).

Cognitive process	Levels
Generalization	Qualitative categorical conception - size
Discrimination	Qualitative relational conception - size
Logical proportional reasoning	Qualitative proportional conception - size
Numerical proportional reasoning	Quantitative proportional conception -scale
Mathematical reasoning	Quantitative absolute conception - scale

conceptions of size and scale and the cognitive processes associated for the operation with these concepts. As shown in Table 1, five cognitive processes are associated with qualitative and quantitative conceptions of size and scale.

The first two cognitive processes for attaining scale cognition are generalization and discrimination among objects of different sizes. From a Piagetian perspective, generalization will depend on the classification of objects, and discrimination will depend on the serial ordering of objects (Inhelder & Piaget, 1958). Both are qualitative processes best associated with categorizing and ordering of "size" of the objects relative to different categories of scale (e.g., atomic, nano, micro, macro, astronomic). To bridge a qualitative conception of size to a quantitative conception of scale, proportional reasoning serves as the cognitive process required to bridge the logical conception of size to the mathematical conception of scale (Inhelder & Piaget, 1958; Magana, Brophy, & Newby, 2008). This bridging process involves multiple comparisons, inference, and prediction, as well as both qualitative and quantitative methods of thought (Lesh, Post, & Behr, 1988). The fifth component of the framework relates to the numerical absolute size of an object, supported by mathematical cognition, for representing numbers and making mathematical calculations to assign an absolute number or measurement to an object (Campbell, 2005).

3. Learning strategies for supporting size and scale cognition by means of multimedia learning tools

To identify specific learning strategies that could help support the cognitive processes associated to the FS2C framework, we used Rosch's Prototype Theory of concept learning (Rosch, 1975, 1978). According to Rosch, a concept is learned and represented as a prototype of a class of objects. A prototype of a class is an image constructed from experiences with examples of the class. The prototype includes the typical features of the class, not all of the defining attributes as the classical theory. After a prototype is formed, newly encountered instances are identified by comparison with the prototype (Klausmeier, 1992). Therefore, a good way to facilitate the learning of an abstract concept would be to generate a reasonable substitute for a prototype by first transforming the attributes of the abstract concept into a more concrete form (Newby & Stepich, 1987). As a result, a prototype substitute will be generated and provide a mental model based on everyday uses and conceptions of size and scale.

Based on this theory of concept learning, we propose three specific learning strategies to support cognitive processes associated with size and scale cognition: integration and differentiation strategies, proportional analogies, and a logarithmic scale metaphor. Although the implementation of these strategies were coupled together to support size and scale cognition as a whole, we considered that some strategies were more well-aligned for supporting more specific cognitive processes than others. For instance, integration and differentiation strategy was well-aligned to support generalization and discrimination; proportional analogies were well-aligned to support logical and numerical proportional reasoning; and a logarithmic scale metaphor was used to support numerical proportional reasoning and mathematical reasoning. In the following section we explain each of these strategies and provide an evidence-based rationale of why each of them was chosen.

3.1. Integration and differentiation

Integration and differentiation can be used as learning strategies to support student generalization and discrimination of objects of different sizes and scales. Integration consists of linking consistent but unrelated conceptions and differentiation consists of highlighting the differences between related concepts (Hewson & Hewson, 1984). Such linkages can increase the likelihood that scientific knowledge will be remembered and by facilitating reasoning. Integration and differentiation are useful strategies that create a situation of conflict, and at the same time elaborate connections among ideas. These learning strategies may result in more robust conceptual structures and avoidance of mixture of related concepts and discrimination between them (Eylon & Linn, 1988).

3.2. Proportional analogies and a scale metaphor

Analogies are fundamental cognitive mechanisms that people use to map processes by identifying relevant information from a more familiar domain to a less familiar one (Mason, 2004). Since early times, the powerful role of analogies has been recognized as a method to enable communication, exploration, and inference about novel phenomena, as well as to transfer learning across subject domains (Gentner & Markman, 1997; English, 2004; Goswami, 2001; Richland, Morrison, & Holyoak, 2006). Gentner (1983) defined an analogy as "a device for conveying that two situations or domains share relational structure despite arbitrary degrees of difference in the objects that make up the domains." English (1997) described metaphors as characterized by cross-domain mappings. The relationship between analogies and metaphors is "like analogical reasoning, metaphorical reasoning can generate new inferences and lead to the construction of mental models based on the relational structure shared by the source and target (p. 7)."

On the other hand, it has been identified that intuitions of proportional reasoning are based on people's ability to recognize relational similarity (Lesh et al. 1988; Singer-Freeman & Goswami, 2001). Similarity and analogy require the same process of comparison, that is, a "structural alignment and mapping between mental representations" (Gentner & Markman, 1997). Because (a) reasoning proportionally and reasoning analogically require the same mapping between mental representations, (b) young children have the ability to reason by analogy, and (c) analogies and metaphors are powerful tools in enabling people to communicate, explore, infer about novel phenomena, and transfer learning across subject domains, *we suggest proportional analogies as a sense-making way to scaffold and emphasize relative sizes of objects in different scales* (Magana, et al., 2008).

Conventional proportional analogies usually take the form of A:B:C:D (English, 2004), where the A and B can be termed as the base or source and C and D as the target (Gentner, Holyoak, & Kokinov, 2001). These analogies are basically proportional or relational problems (English, 2004; Gentner & Markman, 1997). Analogs could be based on everyday uses and conceptions of size with categorical relations, and these conceptions of scaling could be based on experience containing prototypes as exemplars of categories, such as landmarks and reference points (Tretter et al. 2006).

In the context of the instructional materials developed to convey size- and scale-related concepts, a classical conventional analogy takes this form. The difference in sizes between the height of a human (A) and the length of an ant (B) is approximately the same–proportional as the difference in sizes between a bacteria (C) and the diameter of a DNA double strand (D); whereas the height of a human is mapped with the size of the bacteria and the length of an ant with the diameter of a DNA double strand. These proportional analogies may serve as a way to bridge the qualitative (the logical proportional relationship between two objects) to the quantitative (the mathematical proportional relationship between two objects) properties between two pairs of objects. The source pair of the analogy may serve as the size landmark object to express the size of one object in terms of another. Furthermore, by incorporating the scale together with the analogies, students may be able to relate ratiometric relationships illustrating the unitless dimensions of the system to the quantitative measure of scale and its units. The metaphor presented to the students was a logarithmic scale that represented powers of ten. These powers were considered as points on a line (see Fig. 1), and this scale was used to display both the categorical concept of size (nanoscale, microscale, and macroscale) and the quantitative measure of scale, using powers of 10 and SI units.

Based on the assumptions of the Cognitive Theory of Multimedia Learning (Mayer & Moreno, 1998a), we argue that multimedia affordances can provide new possibilities to teach and to learn about size and scale by offering a multimodal and multiscale presentation of information and facilitating sense making at different scales (Magana, Brophy, et al., 2012). Multimedia learning refers to the learner's construction of mental models from printed or spoken words and static or dynamic pictures (Mayer, 2005a, pp. 1–16). The Cognitive Theory of Multimedia Learning (Mayer & Moreno, 1998a) argues that learners possess two information processing systems: visual and verbal. The auditory input goes to the verbal system, and the textual or animation input goes to the visual system. Based on these assumptions, we believe that the proposed learning strategies to support size and scale cognition can be effectively instantiated by means of multimedia learning. In the section below we explain how some or all of these learning strategies were embodied into a selection of three different tools for multimedia learning.

4. Method

This study consisted of a quasi-experimental design where three different interactive multimedia tools for learning were used to convey concepts related to size and scale. These tools were created by three different types of industries and for different purposes. Generation-nano (GN) was created by the Network for Computational nanotechnology, an academic and research organization; Universcale (US) was created by Nikon, a transnational corporation studying light; and Nanoscaling (NS) was created by PlayGen, a UK studio focused on serious games and gamification.

4.1. Participants

The participants of the study included 224 undergraduate students from an introductory educational computing course at a Midwestern university who were divided into sixteen laboratory sessions. The course learning outcomes consist of (a) having students demonstrate their abilities to use computer systems to enhance their own professional growth and productivity, and (b) to apply computer systems to support instruction in their selected developmental and content areas. The sixteen sessions were randomly assigned to one of three different instructional media tools having 74 students using the GN tool, 93 students using the US tool, and 57 students using the NS tool.

We assumed that all participants had similar backgrounds in using instructional technology because the course is taught at an introductory level. Because the class is taught by one instructor and sixteen teaching assistants in each section to run the labs, we also assumed that the students had been exposed to the same instruction throughout the semester. Therefore students from each session were considered equally representative of the entire population of learners in the course. The teaching assistants participated in a training session where all the procedures and protocols were reviewed and explained. This study received institutional review approval and was considered an exempt review.

4.2. Procedures and online tools

The three online tools (i.e., GN, US, NS) selected for this study can be classified as multimedia learning tools that provide visual- and text-based information (the audio is only background music, which is considered incidental to the learning outcomes). Common across all these tools is that each user controls navigation with a computer mouse to access various visual images of objects and text descriptions of the objects, and each tool contains two main components: (a) a set of objects in different sizes and (b) a logarithmic scale indicating the actual size of the object. The three multimedia tools were evaluated by eight expert instructional designers in terms of their potential advantages and disadvantages as described in Magana, Newby, et al. (2012). We present below the description of each multimedia learning tool, the learning strategy embedded in each of them, and a brief summary of the expert evaluation as reported by Magana, Newby, et al. (2012).

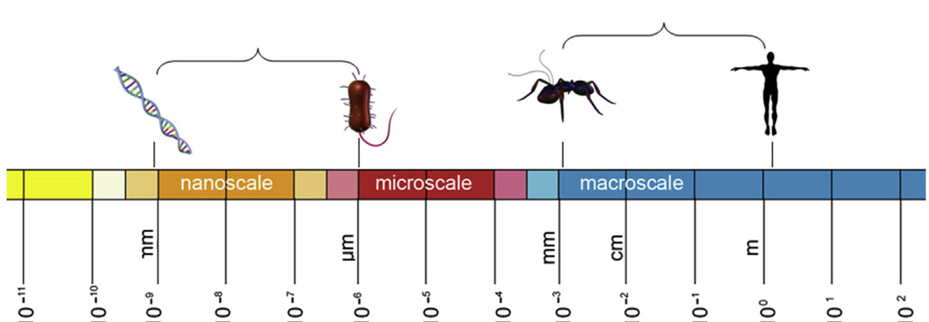

Fig. 1. Scale metaphor and proportional analogy adapted from (SRI, 2007).

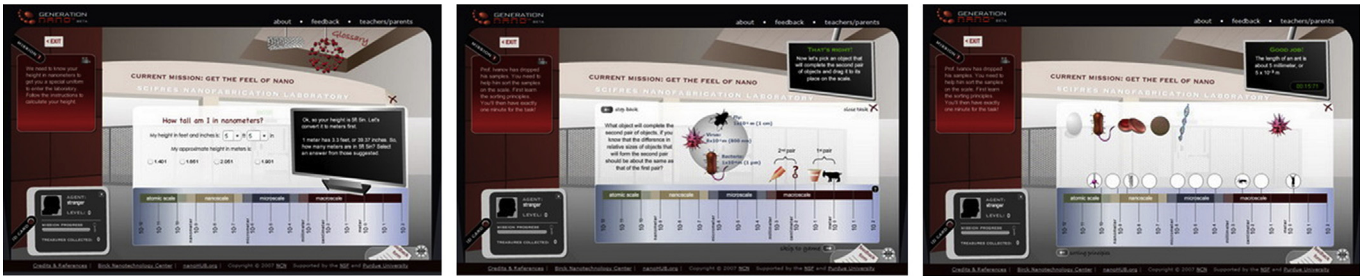

Fig. 2. Interactive features of Generation Nano (GN): copyright Network for Computational Nanotechnology.

4.2.1. GN – Generation-Nano

The first multimedia learning tool, Generation Nano (GN) (Network for Computational Nanotechnology, 2007), is a Flash animation game-like activity designed for learning about various aspects of nanotechnology, including size and scale. This tool was designed based on the FS2C framework and has embedded the integration and differentiation learning strategy, proportional analogies, and the use of a scale metaphor. Integration and differentiation is afforded by a sorting activity of different objects according to their sizes. As part of this sorting activity, users interact directly with a logarithmic scale that, in addition to measures represented as powers of ten, it included labels of the scales (i.e., nanoscale, macroscale) allowing users to identify an object category at the same time they sorted it (See Fig. 2). The proportional analogies are integrated as part of the "learn the rules of the game" activity. This activity uses proportional analogies to have users compare objects, also placing them on the logarithmic scale. Other activities included in the GN Web site have students compute their height in nanometers and observe two objects at different scales (see Fig. 3).

Expert evaluation of the top three perceived advantages and disadvantages of Generation Nano (GN) is presented on Table 2.

4.2.2. US – Universcale

The second multimedia for learning tool, called Universcale (US) (Nikon, 2009), is a Web-based Adobe Flash animation that compared the sizes of objects from the nanoscale to the universe scale by using a logarithmic scale as the main navigation mechanism. By clicking on the logarithmic scale, the user could rapidly index a text description of objects on the scale and see images of other objects in that same scale range. When the scale was clicked on a specific object, an explanation and size of the object was displayed, as shown in Fig. 4. Thus, the learning strategies embedded in this tool are differentiation by comparing different objects, integration by providing descriptions of different realms (see Fig. 4 first feature), and the use of a scale metaphor.

Expert evaluation of the top three perceived advantages and disadvantages of Universcale (US) is presented in Table 3.

4.2.3. NS – Nanoscaling

The third tool used in this study was NanoScaling (NS) (Playgen, 2009). It afforded the differentiation strategy by comparing relative sizes of objects that is similar to the Universcale's, but it also contains 3D graphical images of objects next to each other as shown in Fig. 5. Again, a logarithmic scale provides a frame of reference for the objects and a navigation mechanism to index various sizes of objects along the scale. Users could also click on the objects to obtain more information. Whereas the other applications can be executed in a Web browser, NS is a stand-alone executable program application.

Expert evaluation of the top perceived advantages and disadvantages of NanoScaling (NS) is presented in Table 4.

Prior to interacting with one of these multimedia learning tools, the participants were asked to complete a pretest. Sections were randomly assigned to one of three treatment groups. Participants were given 20 min to interact with one of the instructional medial tools assigned to their group. Lastly, they completed a posttest similar to the pretest.

4.3. Data collection and scoring methods

The data collection of instruments and scoring methods used were the ones developed by Magana, Newby, et al. (2012), which consists of five different tasks aimed to assess different levels of the FS2C framework. For each task, we created a normalized error metric $\varepsilon \in <0,1>$, where ε=1 described an entirely wrong answer and ε=0 a perfectly correct answer. The error ε, however, was calculated differently for each task. The task associated with the FS2C framework and the corresponding scoring method is summarized as follows.

Fig. 3. Generation nano (GN) interactive activities associated with comparing size of part of objects: copyright Network for Computational Nanotechnology.

Table 2
Top three expert evaluators' perceived advantages and disadvantages of Generation Nano.

Advantages	#	%	Disadvantages	#	%
Motivational strategies with potential to keep students engaged	7/8	88%	Strategy for interaction with a single user and not in teams	6/8	75%
Strategies to provide guidance, feedback, and expert advice	7/8	88%	Potential for causing distractions or misconceptions among learners	3/8	38%
A variety of media and interactive features	2/8	25%	Too much text or too many things going on	2/8	25%

Ordering by relative size Task 1 consisted of ordering objects by relative sizes in which students were asked to order a set of 11 objects from smallest to largest. The perfectly correct answer consisted of all objects sorted in their corresponding place according to their relative size from smallest to largest. The error of the entirely wrong answer consisted of the objects ordered in the exact opposite direction. To score all others in between, we calculated a penalty value δ_i^o. We compared each object with the immediate object to its right. If the object was larger, there was no penalty; if smaller, however, we increased the penalty value by one. The penalty for the entirely wrong answer was calculated manually and denoted by Δ^o. The error of the ordering task was then calculated as

$$\varepsilon = \frac{\delta_i^o}{\Delta^o}. \tag{1}$$

Classifying Task 2 consisted of asking students to classify the same set of 11 objects into five bins according to similar sizes. The students were able to select the number of bins they considered appropriate (i.e., from one to five) and asked to label them based on their classification by size. To score this task, we first calculated the displacement of each object δ_i^c from its correct location. The normalized error ε of the answer was then calculated as the sum of the relative displacements of all objects divided by the maximum possible displacement,

$$\varepsilon = \frac{1}{\Delta^c}\sum_{i=0}^{n-1}\delta_i^c, \tag{2}$$

where Δ^c was the maximum possible displacement and δ_i^c the actual displacement of the i-th object. Because of the multiple and arbitrary selection of bins, we decided to have one perfectly correct answer that located objects in four bins with categorizations of objects at the atomic scale, nanoscale, microscale, and macroscale. For all others, the actual value of δ_i^c and Δ^c depended on the actual number of bins, and therefore the calculated error was also dependent on the number of bins. We created an application in C++ that analyzed the data. It first calculated the relative displacement of each object in the answer and then performed the calculation of the error of the answer according to Equation (2).

The absolute measurement Task 3 consisted of two items aimed at evaluating student abilities to estimate absolute sizes of the given objects. A second item asked students to locate two pairs of objects on the scale provided in the form of a proportional analogy. A first pair at the macroscale was denominated as the source pair, and a pair of items at the micro- or nanoscale was denominated as the target pair. This task was scored by comparing the absolute location of the two pairs of objects together with the correct response of the second item. The penalty value δ_i^a was equal to zero if an object was located correctly. If an object was located incorrectly, but the displacement was not significant (i.e., neighbor location), the penalty was set at ½. For all others, the penalty was set at one. The maximum error was the sum of all objects $\Delta^a = 4$. The total error ε was then calculated using Equation (1).

In the logical proportional Task 4, students were asked to identify the proportional difference in sizes between a source pair of objects and a target pair of objects, expecting them to do the correct mapping between the source pair and the corresponding target pair. To score this task, a penalty value was assigned to one $\delta_{\mathrm{flip}}^{\mathrm{l}} = 1$ if the pair of objects was placed in opposite order. The distance penalty was calculated as the Euclidian difference of the absolute distances on the logarithmic scale of the two pairs of objects $\delta_{ij}^m = \sqrt{(\delta_i^m - \delta_j^m)(\delta_i^m - \delta_j^m)}$, where δ_i^m and δ_j^m were the distances of the first and second pair of objects on the logarithmic scale. The maximum error Δ^m is the maximum penalty in the measured set, and the error was calculated as

$$\varepsilon = \frac{\delta_{flip}^l + \delta_{ij}^{ml}}{\Delta^m}, \tag{3}$$

Students were prompted in the numerical proportional Task 5 to identify the relative sizes in numerical terms between two pairs of objects. The penalty measure had three components. First, a penalty of one $\delta_{\mathrm{flip}}^{\mathrm{l}} = 1$ was added if the objects were in opposite order on the

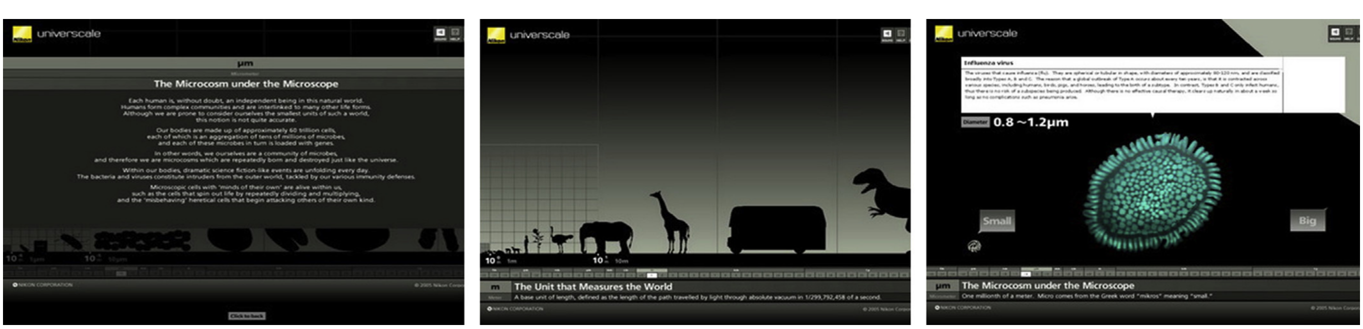

Fig. 4. Interactive features of Universcale (US): copyright Nikon Corporation.

Table 3
Top three expert evaluators' perceived advantages and disadvantages of Universcale.

Advantages	#	%	Disadvantages	#	%
Potential to allow students to compare objects from different sizes on different scales	7/8	88%	Lack of embedded instructional design and learning objectives	5/8	63%
A variety of interactive features	4/8	50%	Contains too much information and is complicated to use	4/8	50%
Clear information provided about the objects	4/8	50%	Eventual loss of motivation or engagement	3/8	38%

scale. If the numerical value was not identified, the penalty was set at $\delta_t^l = 1$. Lastly, if the objects were not located in the corresponding pair on the logarithmic scale, the error of location was set at one $\delta_l^l = 1$. The maximum error Δ^l was the maximum penalty in the measured set. The error was then calculated as

$$\varepsilon = \frac{\delta_{flip}^l + \delta_t^l + \delta_l^l}{\Delta^s}. \tag{4}$$

For tasks 3, 4, and 5, two versions, A and B, of instruments were developed. The difference of the two was the objects used in the test items. A *t*-test analysis was conducted in the pretest scores within each of the categories of the proposed framework, aiming to identify significant differences between versions A and B. No significant differences were found in the level of difficulty between them; therefore tests A and B were considered equally comparable.

4.4. Validity and reliability of the tasks

The tasks went through a process of iterative review and validation. Specific validation measures included (a) comparison between each of the tasks and the task being proposed in existing literature describing similar studies (e.g., Delgado, Stevens, Shin, Yunker, & Krajcik, 2007; Tretter et al. 2006), (b) an expert review performed by a researcher in the area of learning sciences with a research agenda in nanoscale science education, and (c) a recategorization by two independent researchers of each of the designed items of the task related to the FS2C framework. Reliability measures included pilot testing of earlier versions of the instrument with a group of middle-school students.

4.5. Design and data analysis

In this study we used a pretest and a posttest design, featuring three different multimedia learning tools to convey conceptions of size and scale. By means of descriptive statistics, we first briefly describe the pretest data aiming to provide a description of participants' current performance in the five levels of the proposed framework. Then for each level of the FS2C framework, we investigated whether the treatment significantly improved participants' posttest score. We also investigated for any significant differences between the treatments.

A two-way ANOVA was used to test for treatment group effects in participant responses. The considered response was the difference in scores between pretest and posttest for each participant. Therefore each student was his or her own block, removing student-to-student variation from the analysis. The two factors tested were the different Web-based interactive media and the version test participants took (versions A or B). A Tukey multiple comparison procedure was used to control the Type I error rate when examining treatment differences among the interactive media treatments. The assumptions of the model were independent, identical normally distributed residuals with constant variance. Standard diagnostic checks were used to validate the model.

5. Results

The first step in the analysis consisted of describing general trends of student performance on the pretest scores and identifying significant differences for all three groups before being exposed to the multimedia for learning tools. Table 5 summarizes general trends from the pretest and posttest normalized scores. Results from the ordering task indicate an overall positive performance (84% on average) with no significant differences between the three treatments ($F = 0.00$, $p = 0.996$). The classifying task showed inconclusive results on the pretest scores (49% on average) with no significant differences between the three treatments ($F = 0.78$, $p = 0.4591$). Specifically, the students showed limited ability to distinguish between sizes of objects they could not see with their naked eye (e.g., by locating objects from the

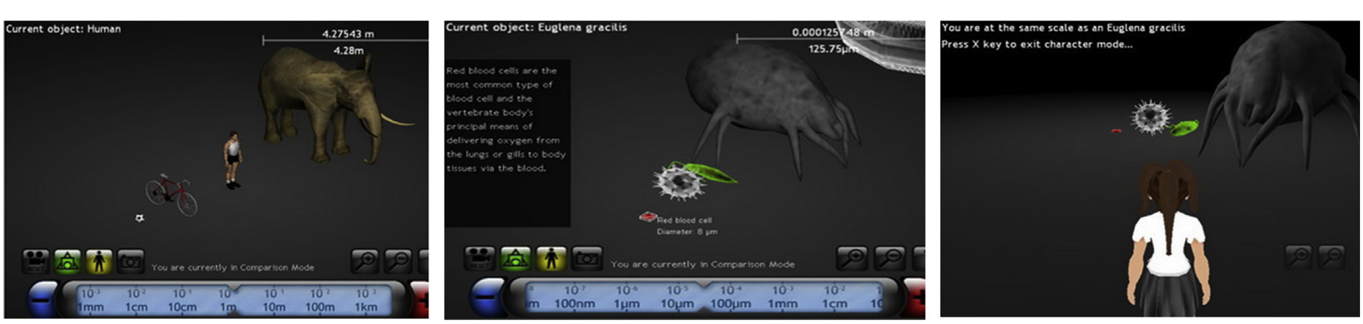

Fig. 5. Interactive features of NanoScaling (NS): copyright PlayGen.

Table 4
Top three expert evaluators' perceived advantages and disadvantages of NanoScaling.

Advantages	#	%	Disadvantages	#	%
Potential to allow students to compare objects from different sizes on different scales	6/8	75%	Lack of embedded instructional design and learning objectives	5/8	63%
A variety of media and interactive features	3/8	38%	Potential for causing distractions or misconceptions among learners	5/8	63%
3D visualization/rotation of objects	3/8	38%	Potential unavailability or unreliability of Internet connection	5/8	63%

micro- and nanoscales in the same category). Concerning logical and numerical proportional tasks, the results suggest difficulties in student abilities to (a) accurately locate objects on a logarithmic scale (48% on average) and (b) identify how many times an object is bigger or smaller than another one (21% on average), especially the bigger the difference is between the objects. In regard to the logical proportional task, no significant differences were found between the three groups ($F = 0.07$, $p = 0.9280$); however, significant differences were found in the numerical proportional task ($F = 6.80$, $p = 0.0013$). Students in the NS group performed significantly lower than those in the US group. Therefore, results from the pretest scores on absolute measurement tasks suggest that students have difficulties in estimating approximate sizes of submacroscopic objects or the size of very large objects (28% on average). No significant differences were found between the three groups ($F = 2.99$, $p = 0.06$). Table 5 also depicts student performance scores in the posttest tasks for each of the three treatments.

The second step in the analysis consisted of identifying which treatments resulted in significant positive differences between the pretest and posttest scores as well as identifying differences among treatments. As shown in Table 5, the three multimedia learning treatments resulted in positive increases from the pretest to posttest scores for the ordering task. Results suggest that NS shows the highest increase on student performance; however, an ANOVA analysis indicated no significant differences between the three treatments on the mean gain ($F = 0.83$, $p = 0.4374$). Student performance on the posttest score for the classifying task revealed an average significant increase of approximately 17% for the three treatments. The three multimedia learning tools resulted in no significant differences in the mean gains ($F = 0.46$, $p = 0.6304$), suggesting that GN, US, and NS were equally effective for the classifying task.

Concerning the logical proportional task, the US multimedia learning tool seems to be the most effective with a significant increase of 11% on student performance. However, the ANOVA analysis showed no significant differences on the mean gain between the three treatments ($F = 1.53$, $p = 0.2192$). Student performance in the numerical proportional task produced mixed results. Although students in GN and NS increased their performance approximately 9%, students in US decreased their performance on approximately 7%. These changes on the three treatments were found to be significant when compared to pretest and posttest scores ($F = 4.31$, $p = 0.0146$).

In conclusion, for the absolute measurement task students in the three groups on average increased their performance, having US and NS showing positive significant differences in the posttest scores. When the mean gains were compared, the two treatments that showed significant differences were GN and US ($F = 4.08$, $p = 0.0181$).

We also performed an ANOVA on the posttest scores to learn if any of the treatments overall resulted in significantly higher scores. No significant differences were found for the ordering task ($F = 0.21$, $p = 0.8126$), the classifying task ($F = 0.19$, $p = 0.8237$), the logical proportional task ($F = 1.74$, $p = 0.1779$), the numerical proportional task ($F = 0.98$, $p = 0.3771$), or the absolute measurement task ($F = 0.77$, $p = 0.4645$).

6. Discussion

This study proposed that learning strategies such as integration and differentiation, proportional analogies and a logarithmic scale metaphor, coupled with affordances of multimedia for learning, can enhance size and scale cognition as prescribed by the FS2C framework.

Table 5
Summary of results from the five FS2C tasks per group.

FS2C task group	DF	Pretest		Posttest		T value	Pr > |t|
		Mean	Std. Dev.	Mean	Std. Dev.		
Ordering							
GN	68	84%	0.11	86%	0.20	−0.913	0.183
US	101	84%	0.13	87%	0.14	−1.520	0.066
NS	57	84%	0.10	90%	0.11	−4.0.468	0.000
Classifying							
GN	68	50%	0.34	66%	0.32	−3.746	0.000
US	105	52%	0.31	68%	0.30	−4.365	0.000
NS	60	46%	0.35	66%	0.32	−4.834	0.000
Logical proportional							
GN	68	49%	0.37	49%	0.38	0.244	0.404
US	105	47%	0.37	58%	0.34	−2.413	0.009
NS	60	48%	0.33	52%	0.39	−0.599	0.276
Numerical proportional							
GN	68	20%	0.23	29%	0.41	−1.958	0.027
US	105	29%	0.29	22%	0.28	1.786	0.039
NS	60	14%	0.20	23%	0.25	−2.312	0.012
Absolute measurement							
GN	68	31%	0.24	32%	0.29	−0.157	0.438
US	105	30%	0.27	35%	0.26	−1.830	0.035
NS	60	22%	0.22	38%	0.29	−4.366	0.000

These learning strategies were instantiated by means of diverse forms of multimedia learning. Below we describe how these learning strategies and multimedia affordances might have impacted student learning of conceptions of size and scale.

6.1. What are learning strategies that can lead to the biggest effect (if any) on students' learning about conceptions of size and scale according to the FS2C framework?

Learning strategies that we considered appropriate to support size and scale cognition, according to the FS2C framework, and which were consistently embedded across the three multimedia tools were the strategy of differentiation and the strategy of using a logarithmic scale metaphor. These strategies were instantiated by means of having users compare and contrast objects of different sizes and the use of a logarithmic scale metaphor to identify ranges of numerical values expressed in powers of ten. The strategies of integration and the use of analogies were only explicitly integrated in the GN tool. The integration strategy took the form of specific labels indicated as part of the logarithmic scale that allowed students to classify objects in different realms. The proportional analogies strategy was integrated as part of the rules to play the game.

The results of the evaluation of the multimedia learning tools suggest that overall, students increased their performance in most of the tasks associated with the FS2C framework after being exposed to the multimedia for learning tools. Considering the average performance in the ordering task, we can suggest that exposing students to comparing objects from different sizes can help them discriminate between their sizes. Differences in the results of the ordering task between groups could be attributed to the way affordances of multimedia were used to implement the learning strategy. These possible effects are explained in the section below. In the classifying task, the average performance scores suggest that the integration strategy may not have had an effect on student learning. Similarly, results from student average performance in the logical proportional task suggest that the use of proportional analogies did not have an effect on student proportional reasoning. A possible explanation for this result could be the way the learning experience meant to introduce the proportional analogies was presented to the user. Specifically, this learning experience was presented as a "learn how to play the game" feature. We believe that this design decision might have caused students to skip the training session and therefore were not exposed to the learning experience. Another possible explanation could be that because explicit indications of the analogies were not provided, the students might have had difficulties identifying them. We believe that GN required explicit instructions on how to employ proportional analogies as a learning strategy to enhance their proportional reasoning. Alternatively, by comparing the results from GN with those from US and NS, we can see that the latter ones had a positive increase in student performance in the logical proportional task. These differences may be attributed to the multimedia learning affordances discussed in the section below.

Considering student average performance on the numerical proportional task and the absolute measurement task, we suggest that the use of the scale metaphor seemed to be an appropriate learning strategy to help students reason numerically. The scale metaphor might have allowed students to identify how many times (in powers of ten) the size of an object was bigger or smaller than another one as well as to make associations between the objects and their approximate measurements expressed in powers of ten. Smaller or negative differences in the average performance between groups (i.e., US in the numerical proportional task and GN for absolute measurement task) can possibly be attributed to multimedia effects.

The effects of the proposed learning strategies could be discussed under the umbrella of a similar study. Tretter et al. (2006), conducted a study to identify the different understandings of size and scale among individuals with different levels of expertise. Based on their findings of the strategies that experts used, Tretter and colleagues proposed that students must create scale mental models focusing on relative sizes and not much on exact size information. These mental models could be based on everyday uses and conceptions of size with categorical relations. In addition, they also suggested that conceptions of scaling must be based on experience, be organized into categories and may contain prototypes as exemplars of categories; such as landmarks and reference points. The uses of size landmarks can be used to anchor ideas of size and scale (Tretter et al. 2006). These landmarks can also be coupled with a process of "unitizing." Unitizing has been referred to as a common strategy to express the size of an object in terms of another object (Lamon, 1996). Based on these findings, we argue that the use of learning strategies that allow students to compare objects from different sizes can help them create size landmarks. In addition, the use of a logarithmic scale may help students relate such landmarks with specific scales that can then be leveraged when engaging in unitizing processes.

6.2. What are The potential affordances of multimedia for learning tools that can lead to the biggest effect (if any) on students' learning about conceptions of size and scale according to the FS2C framework?

Affordances of multimedia learning can help instructional designers implement learning strategies in different ways. For instance, specific advantages of multimedia learning are that it affords self-paced instruction and instant feedback. However, in this study, the different ways the learning strategies were instantiated can potentially explain the variances in the results. We will now describe specific characteristics and principles of multimedia learning that were represented in these tools.

By means of the expert evaluations we can suggest that all three tools embedded the coherence principle (Mayer, 2005b, pp. 183–200) by effectively combining text and pictures. For instance, one characteristic of the three multimedia tools that students could have benefited from was the amount of different-sized objects that were presented, which they were able to compare. A potential educational advantage for US and NS tools could also have been that they presented objects that allowed students to compare actual differences in sizes, a feature that was not provided for the GN tool. Specifically, US and NS might have allowed students to compare sizes between different objects by means of visual aids that could be zoomed in and out, but with GN, this comparison was made only numerically by means of the scale. A second characteristic for all three multimedia tools was the instantiation of a logarithmic scale. Though for US and NS the scale provided additional information for each of the objects, the GN tool applied the *structure*-mapping principle (Mayer, 2005a, pp. 1–16), allowing students to directly interact by dragging and dropping objects to specific locations on the scale, allowing students to map relationships between elements from one structure to another.

A feature that could explain the effectiveness of the US tool in helping students identify the absolute sizes of objects was the additional information provided for each of the objects. As shown in Fig. 4, when a user clicks on a figure, a new screen appears, providing additional information about the specific size of the object (and other additional information). Similarly with the NS tool, when the user drags a mouse over the object, the name of the object is presented together with information about absolute measurement. We believe that although these two features are very similar, with the US tool this information could have been overwhelming for students and might also have caused a split-attention effect (Mayer & Moreno, 1998b), but the NS tool effectively applied the spatial and temporal contiguity principles (Mayer, 2005b, pp. 183–200) to avoid this effect.

Two notable features presented in the US tool were the use of 3D objects, including a rotation of the view, and an avatar feature. Results suggest that the 3D feature with rotation of the camera can provide students with additional affordances that might have allowed students to explicitly compare objects, especially when the camera was rotated to one side and the objects appeared in an overlapping position. However, the addition of the avatar can be considered a potential source for misconceptions because the size of the human avatar was not proportionally consistent with the size of the objects and therefore not considering the congruence principle (Betrancourt, 2005).

The GN tool had the two distinctive learning strategies, one was the use of analogies and metaphors as the training component, and the other was a gaming feature for the practice component. Although the inclusion of training and practice sections are considered good practices for instruction and multimedia-learning principles (pretraining and practice), we believe that because explicit explanations of the analogies and metaphors were not provided, the students had difficulties identifying them. Also, the gaming component of the practice might also have resulted in split-attention effects, having students focusing on winning the game rather than on learning or practicing the concepts. However, we believe that the specific interaction between learner and scale may have enhanced student understandings of absolute measurement. This idea is consistent with Srinivasan and Crooks (2005), who suggested that multimedia is advantageous if it is interactive and if it allows for learner's control.

We proposed that multimedia learning provides new possibilities to teach and to learn about size and scale by offering a multimodal and multiscale presentation of information and facilitating sense making at different scales (Magana, Brophy, et al., 2012). However, curriculum and learning designers as well as educators must consider how different technology affordances can support specific learning strategies in different ways.

7. Conclusion

This study presented an implementation of the FS2C framework for (a) the selection and later implementation of learning strategies to support size and scale cognition, and (b) evaluation of student learning after being exposed to multimedia for learning tools embedding these strategies. The results of this evaluation suggest that overall the students increased their performance in most of the tasks associated with the FS2C framework after being exposed to learning strategies instantiated multimedia for learning tools. Significant increases in student performances were identified for the classifying task and numerical proportional for all three groups. Other significant increases in student performance were found for NS treatment in the ordering and measurement tasks and for US in the logical proportional and also measurement tasks. We believe that differences in average student performance scores on the tasks can be attributed to the way the selected learning strategies were implemented by multimedia for learning.

Although a limitation for this study is our inability to specifically identify the features of each tool that might have resulted in a student performance increase, we believe that allowing students to compare and contrast objects at different scales promoted their size and scale cognition. Furthermore, we consider that these comparisons were assisted through interactive visuals and other aids that specifically allowed learners to compare objects of different sizes. These visual and interactive aids included the use of zoom-in and zoom-out features; comparison of objects in 3D with additional capabilities to rotate the view; added information accessible by mousing over objects, size expressed in scientific notation, interaction directly between the objects and the logarithmic scale, and comparisons and connections explicit between sizes and their numerical representations.

In regard to instructional strategies, we suggest the use of analogies and metaphors as an instructional strategy for conveying ideas of size and scale, if they are explicitly taught. The best approach to use them might be conveying ideas of size and scale through analogies and metaphors by means of direct instruction and complementing it with the use of multimedia for learning. We also recommend eliminating extraneous features, such as the use of sound (if unrelated) and the use of unrelated objects (e.g., avatars), that can potentially become sources of misconceptions.

Acknowledgments

This work was supported in part by the US National Science Foundation via Award # 0817486 and EEC-0634750. Support from the College of Technology and from the Network for Computational Nanotechnology at Purdue is also gratefully acknowledged. The author wishes also to thank Sean Brophy for his support in collecting the data, Bedrich Benes for his support in processing the data, and Karla Sanchez for her support in verifying the data analysis.

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