Student awareness of conceptual variations in a key nanoscience concept: Conceptual change in an engineering course

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***Abstract**: Along with the rapid development in nanoscience/engineering, the need to educate students to become more proficient in the big ideas of this field has gained enormous attention from scientists and the general public. Consequently, two interventions designed to help students in an engineering design course become aware of conceptual variations of Size and Scale were developed. This study reports findings of a study that examined the impact of these interventions on students' conceptual development. Conceptual changes were assessed by analyzing students' pre and post responses on survey items and through interviews. The analysis reveals the positive influence of the interventions on students' awareness of the conceptual variations in understanding Size and Scale.*

Introduction

The enormous societal attention which nanoscience/engineering has received has raised an urgent need for preparing students to be proficient and scientifically literate citizens in the field (Roco & Bainbridge, 2001). The National Center for Learning and Teaching in Nanoscale Science and Engineering (NCLT) was established to this end and preliminary studies from the center suggest the importance of 1) identifying concepts that are central to developing a solid understanding of nanoscience, 2) unpacking the different ways in which students understand those concepts, 3) assessing potential learning difficulties in understanding the concepts, and 4) preparing/designing appropriate instructional interventions. First, NCLT identified "big ideas" that are thought to be key to the development of nanoscience understanding (Stevens et al., 2007a; Wansom et. al. 2008) and has begun to explore students' conceptual understanding of them (Stevens et al., 2007b; Delgado et al., 2008, Light et al 2008). Indeed, building on the latter studies, Swarat et, al. (submitted in 2009) describe a typology of four types of student understanding of "Size and Scale" informed by variation theory (Marton & Booth 1997). The study identified four key undergraduate conceptions of "Size and Scale" in the nanoscale context: fragmented, linear, proportional and logarithmic.

According to variation theory, learning occurs when a student becomes aware of important differences or variations in the understanding of a phenomenon or concept that they have not been able to discern previously. Interventions making these variations salient to students have been developed and have been shown to enhance students' conceptual development as they become aware of the variations (Ingerman, Linder, & Marshall, 2007; Marton & Pang, 2006). Based on findings from the above studies revealing variations in students' understanding of "Size and Scale" two instructional interventions were developed for students in an introductory engineering design course at a U.S. research University. Taking a focused active learning approach, the interventions aimed to help students become aware of the variations in the ways the concept was understood at the undergraduate level (Marton & Booth, 1997; Marton & Pang, 2006). In order to achieve this goal, students were asked to reflect on their own understanding against a range of alternative conceptions derived from and illustrated by data from the aforementioned study.

An open-ended survey, including three previously validated items (Light et al., 2008) asking students to choose an appropriate scale for objects of widely varying sizes, was administered before and after the intervention. In addition, eleven of the 16 students participated in a follow-up interview, in which they compared their own pre- and post-survey responses and explained the meaning and reasons for the changes.

Methodology

Subjects and Class Context

Sixteen freshman students in an engineering course for majors participated in this study. The course was designed to facilitate user-centered design and communication skills within the nanoscience context. The course was taught by four instructors: two in science/engineering, one in communication, and one in education. The students in this course were asked to work in small groups to develop instructional modules in nanoscience for middle school science teachers. The modules included lesson plans for instruction and the students' work was presented to the class. On the first day of class, background information about nanoscience/engineering was introduced to help students be familiar with the nanoscience context. Two interventions were designed to make students be aware of particular aspects of variation in conceptions of “Size and Scale.” The two interventions were given together on consecutive days and that there was no control group. Although the nanoscience context was provided in this design course, learning objectives of the course are not gaining science content knowledge but building design and communication skills. All of the course assessments were designed for that purpose.

Interventions

Based on the above typology of students’ understanding of “Size and Scale”, two related interventions were designed to facilitate a deeper understanding of “Size and Scale” By helping students discern key aspects of variation, the interventions primarily focused on two key aspects of variation between: scale as a ‘continuum’ distinguishing type 1 and type 2 conceptions, and scale as ‘proportional’ distinguishing type 2 and type 3 conceptions. The five types used in this intervention can be found at the appendix.

Intervention 1

Students participated in sets of exercises and discussions focused on revealing aspects of variation in the conceptual understanding of 1) a proportional versus a linear scale and 2) scale as continuous versus fragmented.

In the first activity, students were asked to place a set of 9 objects (ranging from the radius of Proton to the height of T-rex dinosaur) by using a means of visual representation (number line, graph, chart, table, etc) and then to compare the relative size differences by subtraction or proportion, and explore their relationship to linear and proportional scales. Change in their representations was discussed in small groups and with the whole class. For the second activity, students were instructed to group pairs of objects based on numerical sizes, proportional size difference, and absolute size difference. Differences in how objects were grouped and the relationships between the grouping and scales were the main subject of discussion. In order to explore student conceptions of “Size and Scale” not only at the smaller range but also at the larger range, a final question asked students to compare sizes of earth-apple-atom in different ranges by using analogy.

Intervention 2

In order to heighten students' awareness of the prevalence of alternative conceptions in science, a video documentary, "a Private Universe" (Schneps & Sadler, 1988), was viewed and then discussed. After reviewing the nature misconceptions in general, results of an educational research study (Light, et al, 2008) representing various students' conceptions of "Size and Scale" were introduced. At last, the students in the course were grouped into four groups and each group was given two (of five) selected interview responses and diagrams from the original research study (Light et al, 2008) to analyze. The two interview responses for each group were specifically selected to illustrate one aspect of variation – that is, they were selected because they differed by one aspect of variation. Group one compared response types 1 and 2; group 2 compared responses 2 and 3; group 3 compared responses 3 and 4 and group 5 compared responses 4 and 5. The four student groups were asked to identify the variation between the different conceptions respectively illustrated in their two examples. Each small group then reported back their results to the entire class.

Assessments

Surveys and interviews were used to evaluate students' conceptual change with respect to the interventions. Fifteen students completed both pre- and post-intervention surveys and eleven participated in follow-up interviews.

Three open-ended multiple choice survey items (Light et al., 2008) were administered to assess students' conceptual understanding of "Size and Scale." The first item, designed to assess their understanding in terms of three understandings of scale fragmented, linear and logarithmic scale, asked students to choose an appropriate scale for a list of objects in widely varying sizes. The second item, designed to assess their understanding of the use of units with scale, asked students to choose a scale from a list of scales exhibiting different sets of units. For the third item, to assess students' understanding of certain phenomena associated with widely different sizes, students were asked to choose an appropriate response explaining the properties of objects in the macro- vs. the micro-range. One to two weeks after the interventions, interviews were conducted and students were asked to compare and explain their pre- and post-intervention survey responses with reasons for any change in their responses; and to reflect on whether and how the interventions impacted their understanding of "Size and Scale."

Data Analysis

Survey responses were coded in two ways: 1) following a 0-5 rubric that differentiated levels of conception (5 most sophisticated), and 2) using an eight conception typology (Swarat et, al., 2009). Multiple-choice and written survey responses were analyzed holistically to evaluate whether conceptual understanding changed from pre- and post-survey. Responses were graded by two researchers. Inter-rater reliability (percent agreement) averaged above 60%. All the discrepancy was resolved by discussion and consensus was achieved. The same researchers conducted interviews and then, reviewed the interview transcripts. The interview analysis focused on the following three themes: 1) clarifying students' conceptions of "Size and Scale" represented in pre and post-intervention surveys 2) identifying general reflection on the interventions, and 3) exploring specific conceptual changes attributed to the two aspects of variation: continuum and proportion. In those cases where the data suggested inconsistent conceptions across the 3 items, multiple codes from the typology were assigned. Inter-rater reliability was measured by calculating the percent agreement of line-by-line coding of two randomly selected students' interview transcripts. The average agreement between the two researchers was 88.6% (62 out of 70 codes).

Study Findings

Surveys

Although the mean score for students after the intervention was significantly increased from 1.19 points (39.6% correct) to 2.06 points (68.8% correct, $t=4.34$, $df=15$, $p=0.001$), the mean pre-holistic score averaged across three "size and scale" items was 2.33/5 compared with 2.48/5 for the post. This difference was not statistically significant. ($t=0.49$; $df=15$; $p=0.627$). The smaller gain in holistic score may be partially be explained by insufficient justification revealing students reasoning for their multiple choice answers particularly on their post survey responses where time and engagement were critical factors.

Interviews: Change in Awareness in Aspects of Variation of Student Conceptions of Size and Scale

Post intervention interviews with eleven students were conducted to explore the impact of the interventions on students understanding of "Size and Scale." The interview analysis revealed that seven of the eleven students in this study essentially held logarithmic conceptions of "Size and Scale" before the interventions and these conceptions were retained afterwards. The four students showed from fragmented (1) to linear (1) and proportional (2) conceptions of "Size and Scale." Due to the characteristic of students in this study, analysis of student responses indicated that the change which they experienced centered on changes in their awareness of the key aspects of variation of equally spaced spacing (log scale system) along with continuum and proportion. Table 1 represents the eleven students' pre- (PR) and post (PO)-intervention conceptions of "Size and Scale" and patterns of changes. Changes in their conceptions were marked by arrows and different colors in the Table 1.

Scale Type	Fragmented		Linear		Proportional		Logarithmic	
Conception / Student	4b	4a	3b	3a	2b	2a	1b	1a
AH							PR	PO
BA			PR				PO	
CK						PR		PO
KR						PR /PO		
KS							PR	PO
MG						PR/PO		
PC						PR		PO
PP							PR	PO
RG							PR	PO
TM	PR					PO		
ZP							PR	PO

Table 1: Patterns of change by aspect of variation (PR: pre & PO: post)

First, about the aspect of 'continuum', interview data exhibit that no students held the fragmented view for "Size and Scale" conception. However, student' awareness of the aspect, continuum, was obtained in five student responses (KR, PC, PP, TM and ZP). The students mentioned the importance of the aspect to better understand "Size and Scale." In addition, they considered the fragmented view of scale conception as a misconception that can be often possessed by students. Those indicate students' awareness of conceptual variations with respect to the aspect of 'continuum.'

- **Aware of difference - KR**: I want to say this is correct (*pointing to B on item-1, a fragmented scale*) and I guess, I first was made aware of that… by someone saying oh macro, micro, nano… it's not really a different world. You have to look at it like a continuous spectrum. And then I thought about it and it made sense. So by eliminating B, the second time around, I realized you could use – you could represent it graphically using – or no, by eliminating it, B, I realized you couldn't – you wouldn't necessarily represent them by using different numerical scales of measurement.
- **Aware of difference - ZP**: I just think that having that idea they're not three separate worlds, just one continuous scale. There are no boundaries between those worlds is the most important thing to keep in mind….It's a continuous scale and there are no boundaries…..it's very easy to get into the trap of thinking of them as totally separate worlds…so that's probably the biggest thing.

Second, in terms of the aspect of proportion, two students (KR and MG) held proportional "Size and Scale" conceptions before the interventions did not make change in the post-intervention responses. A student (TM), in particular, made conceptual development from Linear to Proportional scale.

- **Made conceptual change - TM** (pre-survey): The football field and elephant should be close together, then there should be a lot of space before hair, and virus and atom should be close together after hair

  TM (Interview): I just thought about it in that way more so, yeah. So if you look at here: 4 x 10^-7, that would be one, two (*counting*)…4 x 10^-10 or (*correcting himself*) 1 x 10^-10, so there's actually a discrepancy of three decimal places between the two, so they're actually not that close together, so I ended up feeling that this is a pretty good representation. **I**: for the three decimal places, you made some calculation between objects by using numbers. Was this space meant the difference? **TM:** Right, yeah I mean to some degree – a good estimate of it, I suppose.

Third, by being aware of the meaning of even space in logarithmic scale, a student (BA) made conceptual change from Linear to Logarithmic scale and two students (CK and PC) changed conceptions of "Size and Scale" from Proportional to Logarithmic. The two students (CK and PC) pointed out the importance of the even spacing aspect to better understand "Size and Scale." Five students held logarithmic conceptions in the pre-responses (AH, KS, PP, RG, ZP) made slight change within the same logarithmic scale dimension.

- **Made conceptual change – BA** (pre-survey): The difference between smaller objects is very small that it's not very noticeable**.**

  BA (Interview): The first one I didn't know about the logarithmic scale yet, so I chose it in terms of its actual size. **I**: You mean number A is based on the actual size? **BA**: Like football field would be a lot bigger than me, so I thought these are like really, really small, so they'd be close together and it goes on and then it goes up to really huge size – football field. So I looked at the difference in power…

  BA: I mean same scale, like still in the meter scale. But if you go down to the hair, the virus, and the atom, the difference in power is a lot bigger. Like this one is like (*counting*] one, two, three, four, five, six, seven, eight, nine, ten. (*counting another*) One, two, three, four, five, six, seven. So it's like 3, the power of 3, the difference of a power of 3. **I:** What do you mean "difference"? **BA**: Exponentially.

- **Aware of difference - CK**: I wasn't really thinking so much along the lines of 'Oh, it's basing by the difference in the logarithmic exponents.' The first time I was thinking along the lines of the actual difference in size, and not so much the ratio.

- **Aware of difference - PC**: Yeah well, linearly – anytime you have to graph something when, like – similarly in any other class like supposing in Chem, you take a lot of data points like in the beginning of something and then you space them out later. Like sometimes the linear plot isn't the best because to show the change in whatever you're measuring, it just might show all your data bunched up in one spot. Like if we did this linearly, like, it wouldn't exactly look like A, but it would look more so like A except, I mean, the virus and the atom – like the tick marks for those would practically be on top of each other. And that's just not practical, so… **I**: Ok. **PC**: I mean it's correct, but it's not practical. And…

  PC: Yeah like…elephant to football field – that's maybe 1 and ½ powers of 10, so maybe this would be like a meter. **I**: Where the red mark is? **PC**: Yeah, like 1 meter. And then, you go down – like this would be diameter of a human hair is ½ a millimeter. **I**: Half a millimeter? **PC**: Like so this is the way millimeter would be. And the virus… **I**: Why don't you just mark it as decimeter? **PC**: …The virus is a little less than ½ a micron, so…alright, I put that tick mark in the wrong place…but you would have like equally spaced tick marks if I was artistically capable. And each tick mark would be a smaller power of 10. **I**: Ok. So it would be like 10^5, 10^4 – is that what you mean? **PC**: Yeah well, since most of the scale is less than 10^1 it'd be 10 – like, this is 10^0. And then, so you'd have 10^3…-3…10^-6 over here…10^-9, the nanometer. Then you'd have your angstrom like...

Conclusion

There are many studies explored students' conceptions that are often conflicting with what is agreed by the scientific community. Students' conceptions in the studies provide information understanding how students learn and what difficulties in their learning are (Driver & Easley, 1978; Osborne, Bell, & Gilbert, 1983; McCloskey, 1983; Eylon & Linn, 1988; Clement, 1983; Gilbert, 1985). By employing the phenomenographic approach used in Marton and Pang's study (2006), this study also explored students' conception of "Size and Scale." The conceptual variation typology acquired from previous studies provides a spectrum of how students conceive the particular concept, "Size and Scale" (Swarat et al, 2008). Moreover, it became an appropriate tool to assess students' conceptions in the following interview and surveys. The students' conception of "Size and Scale" ranged from unsophisticated fragmented conceptions to more sophisticated logarithmic conceptions, with the majority of them demonstrating more advanced conceptual understanding prior to the intervention. Nevertheless, their interview responses support students' awareness of the critical aspects of conceptions in more advanced categories. These findings suggest that the intervention improved their understanding of "Size and Scale" along several aspects of variation, in particular continuum, proportion and even spacing, as identified in the previous study (Light et al., 2007). In addition, interview responses in this study provide rich information to better explain students' conceptions in proportional and logarithmic scale types. Table 2 summarizes five patterns of changes found in this study.

Patterns of change	Students
Fragmented → Proportion	TM
Linear → Logarithmic	BA
Proportional (no change)	KR, MG
Proportional → Logarithmic	CK, PC
Logarithmic → Logarithmic	AH, KS, PP, RG, ZP

Table 2: Patterns of change

In general, Results of this study suggest the potential of such an intervention in helping students develop more sophisticated conceptions of "Size and Scale" through learning activities as their awareness of conceptual variation in the concept is enhanced. Especially for students in advanced levels of science and engineering, features differentiating conceptions under proportional and logarithmic scale can be important factors required in developing assessment items and instructional materials.

The findings of this study are limited because there was no control group. Therefore, we cannot establish unequivocally that the changes in conceptions are directly attributable to the interventions and not the coursework. To address this issue, a randomized controlled trial to evaluate the impact of the intervention has been planned for the 2008-9 academic year. In addition, to measure whether learning can be transferred into other situations effectively, further studies are required.

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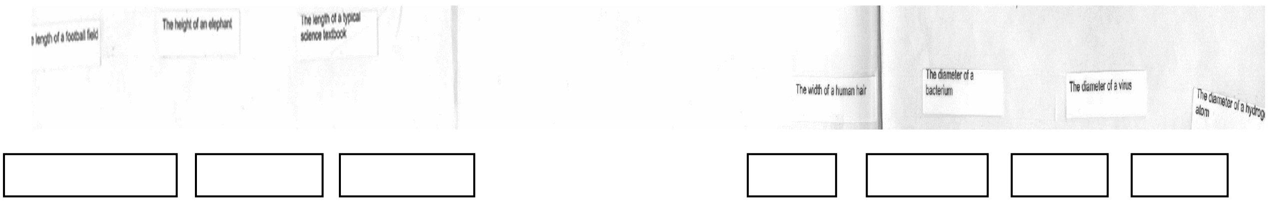
Copyright statement

Appendix

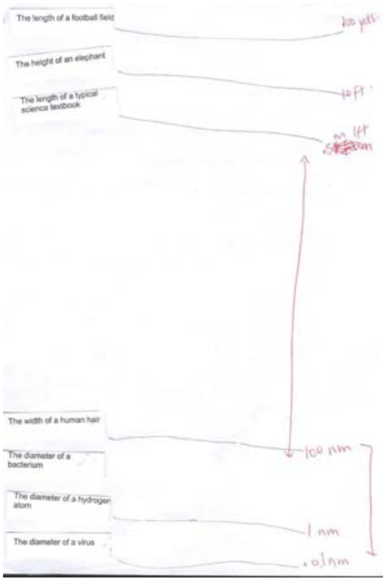


Interviewer: Ok, if you were to rearrange these cards a little bit to actually use the distance between these objects to show their relative differences, how would you change this?

Student: These (pointing at the smaller end of objects) would be like way over here, and there would be a sizable amount of difference between them (pointing at the smaller and the bigger objects). And these (pointing at the bigger objects) would be like way over here on the other side because they are such different in size. Even textbook and human hair, it's like a huge difference between that, more than say between the textbook and the elephant.

(Note: Now the student is constructing the scale over two pieces of paper, as one is not big enough for him.)

Figure 1. Example response type 1 (Fragmented scale)

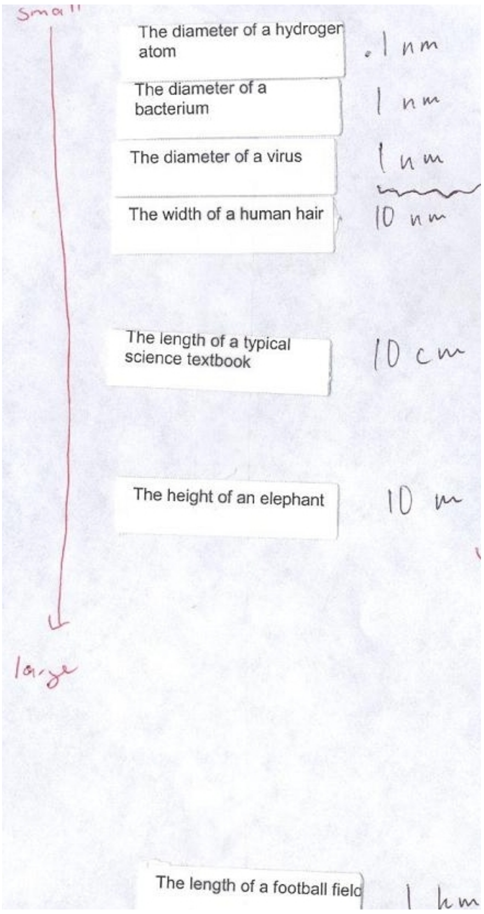


Student: There are different levels of scale. There is something like an object like a bridge, that you might refer to objects that had that scale. You might be working with things that are much smaller, like the processing chip for a computer, which is on a much smaller scale.

.... *(At this point, we asked him what would help him understand the idea of scale.)*

Student: Eh, I think trying to determine the point where macro and micro objects are distinct would be helpful, because there is never a clear-cut example of when something moves from being existing in the macro scale to existing in the micro scale.

Figure 2. Example response type 2 (Fragmented scale)



Interviewer: so when you are, put a, drawing this line here, did you have a numerical scale in mind?

Student: Umm….yes. I knew that this one (referring to football field), right off was the biggest with 100 yards and then, I knew this (referring to atom) was about a tenth of nanometer, so in between those, I sort of assume that they are <u>multiples of ten</u> because it seemed logical to me. Because a textbook I would say is about 10 inches long and I would think [elephant] could be about 10 feet or so, I know the human hair is about, I think, Professor McCormick says maybe about 10 nanometers, so I figured they're multiples of ten.

Interviewer: So if you were to draw a scale that represents this "multiple of ten" idea, would you change your line here?

Student: Change isn't being from vertical to horizontal (referring to the orientation of the graph)?

Interviewer: No, in terms of space… (referring to the space between objects)

Student: Eh, probably not. It maybe makes them a little bit…. Well, actually maybe, maybe do these ones (referring to the sub-macro objects) closer together.

Interviewer: Why is that?

Student: Why is that? Because they are closer in size and proportion than these ones (referring to the macro objects) would be, and then maybe spread them out a little bit more like that. I was thinking of numbers involved. Because these (referring to the sub-macro objects) are very, very close and umm….it is as far as maybe, they are all less than a millimeter even, and then you start to get in into inches or close to meters, centimeters and then meters, and then close to kilometers.

Interviewer: So the logical, the power of ten here would take place during this big jump?

Student: Yes, so in the powers, these (again, referring to the sub-macro objects) would be very, very close together, I can make them close together, probably I would, but you wouldn't be able to read it

Figure 3. Example response type 3 (Linear scale)

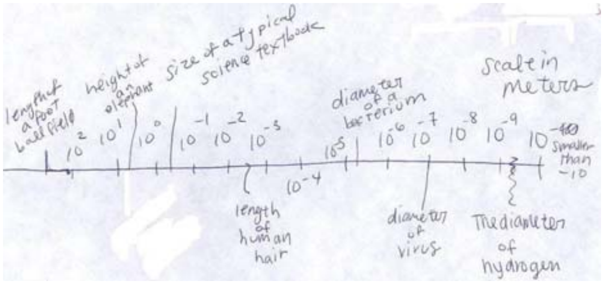


Figure 4. Example response type 4

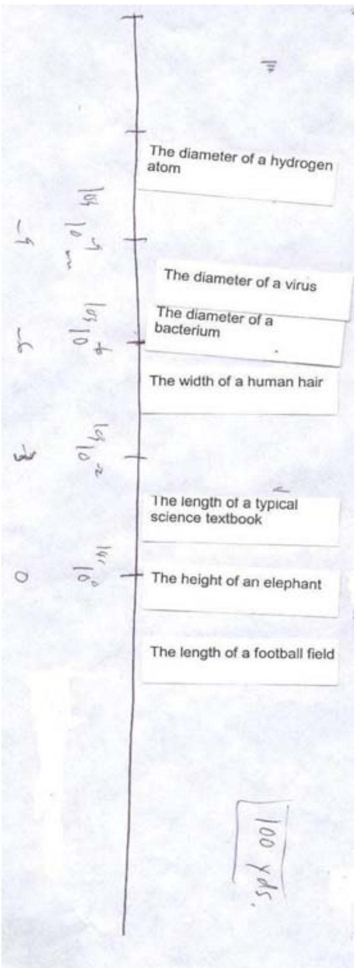
(Detached logarithmic scale)

Interviewer: So what does each of these equal distances represent?

Student: I don't think it represents anything besides that it's in chronological order, but it just kind of represents a scale that people can see. I didn't, when I made it, I wasn't really thinking about making the markings, the difference between the markings, like the relative to the size. I just thought I'm going to put these in order and maybe in context.

Interviewer: That's fine. I'm just trying to understand a little bit better.

Student: Yeah, I don't know how to explain it. This is the way we've been shown the scale, like I've seen this scale at least 12 or 13 times. It's always like in this way. I know down here it gets so small that you can't really see the scale any more, but even here I think to just keep the consistency and not to confuse us, they do it so that it synchronized



Student: Like if you are doing a regular scale, millimeters and micrometers would be really, really small, and meters would be really big… In terms of numerics…you wouldn't be able to see everything on the same scale. All these things *(referring to the sub-macro objects)* would be crammed in there, and you wouldn't be able to tell. The log scale, everything is more evenly spaced.

Figure 5. Example response type 5

(Logarithmic scale)