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The Effect of Color Choice on Learner Interpretation of a Cosmology Visualization

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Abstract

As we turn more and more to high-end computing to understand the Universe at cosmological scales, dynamic visualizations of simulations will take on a vital role as perceptual and cognitive tools. In collaboration with the Adler Planetarium and University of California High-Performance AstroComputing Center (UC-HiPACC), I am interested in better understanding the use of visualizations to mediate astronomy learning across formal and informal settings. In this research, I use quantitative methods to investigate how 122 post-secondary learners are relying on color to interpret dark matter in a cosmology visualization. The concept of dark matter is vital to our current understanding of the Universe, yet we do not know how to effectively present dark matter visually to support learning. I employ an alternative treatment post-test only experimental design, in which members of an equivalent sample are randomly assigned to one of three treatment groups, followed by treatment and a post-test. Results indicate a significant relationship between the color of dark matter in the visualization and survey responses, implying that aesthetic variations like color can have a profound effect on audience interpretation of a dynamic cosmology visualization.

1. INTRODUCTION AND PROBLEM

1.1. Visualizations as Learning Tools for Cosmology

Dynamic visualizations (see Note-1) are learning tools for presenting complex and rigorous science content, without high linguistic demand. They are flexible media that can bring the hidden aspects of the Universe into students' experience and inculcate students into some of the tools of science. Multimedia simulations and visualizations have been shown to support science achievement in biology (e.g., Kiboss, Ndirangu, and Wekesa 2004) and chemistry (e.g., Ardac and Akaygun 2004), so there is precedent to suppose that they might be used to support learning in cosmology. Visualizations can take advantage of "the power of alternative formats in communicating ideas" (Lee and Fradd 1998, p 17), especially for learners who come from non-mainstream cultural and linguistic backgrounds. We also know that such simulations and visualizations can serve to help students generate their own mental images and deepen their engagement in conversations around the content (Wu, Krajcik, and Soloway 2001).

Over the last decade, advancements in technology have made these tools easier to produce and disseminate; modern visualizations are visually stunning and incredibly accurate depictions of the Universe. As a result, real scientific visualizations have become one of the most utilized media for presenting astronomy content in both informal settings and classrooms. Even astronomy education in the K-12 classroom increasingly relies on high tech computer visualizations (Mintz, Litvak, and Yair 2001).

[1]Although I use the term "visualization" for the remainder of the article, I am referring to animated data simulations, or dynamic visualizations, not static representations of data.

Right now, these visualizations are being produced by the scientists who analyzed the data, in ways that make sense to them. Visualizations are socioculturally situated tools (Vygotsky 1978), and thus we cannot take it for granted that what makes sense to some will make sense to others. There is very little research that provides guidance for how to produce visualizations in a way that makes them more effective tools for supporting learning. I am interested in better understanding visualizations as tools that mediate cosmology learning (Engeström 1987; Nardi 1996), in order to guide visualization production to expand access to cosmology content.

1.2. Visualizations and Color

Learners bring a lifetime of experience and knowledge to the table (Piaget and Inhelder, 1969), which makes a profound impact on how they interpret their world. As a classic example, when presented with two images of a star, one red and one blue, learners will take blue to mean cold and red hot, even after being taught the opposite (Carvalho and Sampaio 2006). This is because our sinks and showers, to which we are exposed multiple times every day, tell us otherwise. A lifetime of prior associations is a powerful thing, and without attention to the social and constructivist nature of learning (see Note-2) even the best explanations of color and temperature can be ineffective in convincing learners that blue indicates a higher temperature than red. It is vital that educators be aware of associations like this one, and work patiently with students to support a deeper understanding of science content, especially for students from non-dominant cultural and linguistic backgrounds (Lee and Fradd 1998; Solano-Flores and Nelson-Barber 2001).

It is logical to assume that such prior associations with color come into play in a variety of visualizations, in particular for the invisible aspects of the Universe, for which all color assignments are inherently false. For example, dark matter is vital to our understanding of the Universe (Abrams and Primack 2011), and yet it is invisible. There is no research that suggests how to illustrate dark matter in a way that makes sense to people. The research I present here investigates the effect of color on learners' interpretation of dark matter in a cutting edge visualization produced by the University of California High Performance Astro-Computing Center (HiPACC) for the Adler Planetarium. The visualization, known as the Constrained Local UniversE Simulations (CLUES), reproduces the formation of dark matter structure of our local Universe over time.

The version of CLUES produced for the Adler Planetarium was originally rendered in white and blue, with white representing dark matter and blue representing empty space (as shown in Figure 1 in Section 2.1). In the summer of 2011, I spent a month at the Adler gathering pilot qualitative data about CLUES and other visualizations embedded in their new planetarium show. During this time, I noticed anecdotally that several audience members appeared to be confused by which part of the visualization was dark matter. This led me to the following quantitative research question: *Do changes in the color of a visualization of dark matter affect the way visitors interpret the content?* The quantitative research reported here was conducted in spring of 2012, based on new data collected from college students in California (both at a large research university, and a rural community college).

2. METHODS

2.1. Research Design

To test the effect of color changes on learner interpretation, I designed an internet survey, which is attached in the Appendix. I gave this survey to 122 postsecondary students in California. The survey played the CLUES visualization with accompanying explanatory text (see Note-3), and then asked participants to respond to questions about the visualization. Three versions of CLUES were tested: the original version, which I refer to as "CLUES blue," a color-inverted version in which the dark matter looks brownish-orange, which I call "CLUES peach," and a color-inverted version where dark matter is represented in black on a white background, which I call "CLUES b&w." Snapshots from each version are included in Figure 1.

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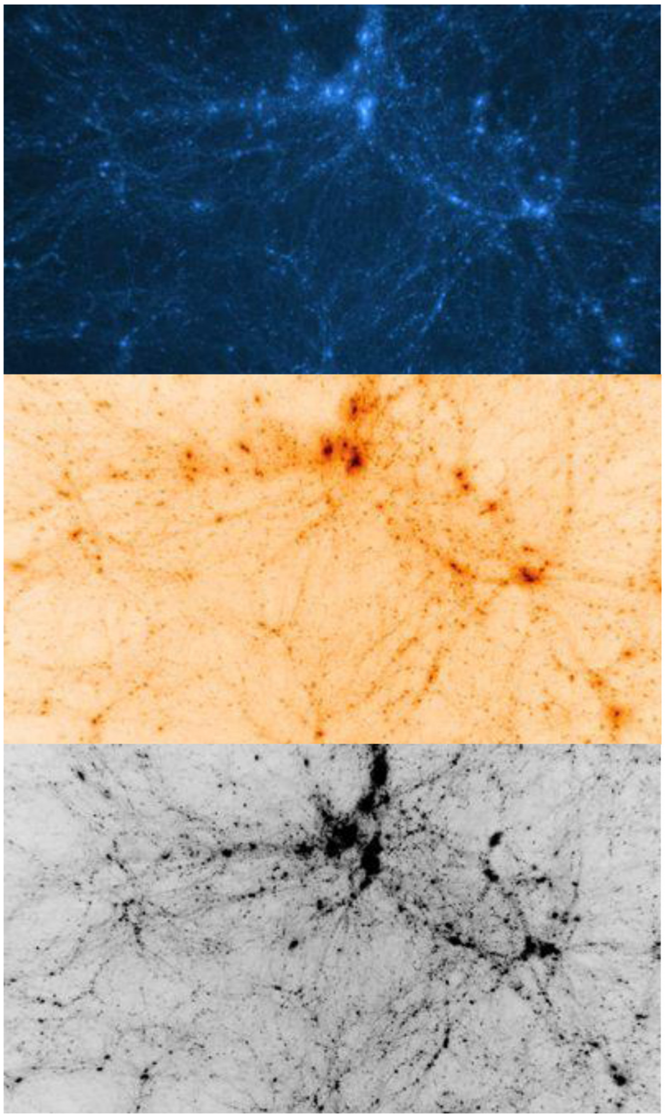
[2] Although learning theory is not discussed in this paper in detail, my work comes from the neo-Vygotskian perspective that all knowledge is socio-culturally constructed and that learning is situated. From this perspective, teaching should be aimed at supporting students as they construct understanding through activity that is mediated by social and cultural tools. Please see Vygostky (1978) and Engeström (1987) for more details.

[3] The explanatory text is included in the Appendix. The visualization can be seen in its original form on the HiPACC website (http://hipacc.ucsc.edu/v4/media.details.php?mediaID=MzRiNjNkODYxYTIz) or in all three forms at Clues Blue (original version): http://youtu.be/2zQuzSHw5RU; Clues BW: http://youtu.be/kr8ylJChgWk, and; Clues Peach: http://youtu.be/doFLj-VIZKM



Snapshot from CLUES Blue

Snapshot from CLUES Peach

Snapshot from CLUES B&W

Figure 1. Snapshots of the three versions of CLUES tested. From top: CLUES blue, CLUES peach, and CLUES b&w. Courtesy of UC-HiPACC, NASA, and the Adler Planetarium

The research presented here is characterized by an alternative treatment post-test only experimental design (Creswell 2003), in which members of a sample are randomly assigned to one of three treatment groups, followed by treatment and a post-test. This design is illustrated in Table 1. Participants were randomly assigned a different treatment by a random number generator built into the entrance website. Each group was shown a different version of the CLUES visualization, the treatment variable, and then asked a series of standardized questions to assess their interpretation of the visualization. These included four multiple choice questions requiring participants to choose the color corresponding to (1) dark matter, (2) stars, (3) empty space, and (4) hydrogen gas, or to indicate that the thing in question was not visible in the visualization.

Other questions included gender, race/ethnicity, first language, education level, familiarity and interest in science and astronomy, and familiarity with similar visualizations. Those participants who responded that they had been diagnosed with colorblindness, or suspected they might be colorblind ($n = 2$), were removed from the sample.

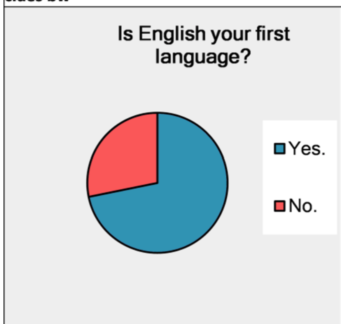
Table 1. Experimental design overview. Xn represents the three treatments, CLUES blue, CLUES peach, and CLUES b&w

Group A:	Random assignment ————	Treatment X1 ————	Observation
Group B:	Random assignment ————	Treatment X2 ————	Observation
Group C:	Random assignment ————	Treatment X3 ————	Observation

CLUES Blue

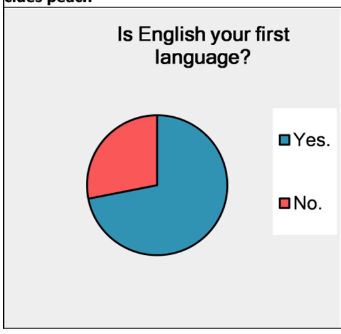
With which ethnic background do you most closely identify:	
Answer Options	Response Percent
Hispanic/Latino	35.9%
Black	2.6%
White	38.5%
Asian/Asian American	7.7%
Pacific Islander	0.0%
Native American/American Indian/Alaskan Native	2.6%
Multiracial	15.4%
Other (please specify)	7.7%

clues bw



With which ethnic background do you most closely identify:	
Answer Options	Response Percent
Hispanic/Latino	28.9%
Black	0.0%
White	42.1%
Asian/Asian American	18.4%
Pacific Islander	0.0%
Native American/American Indian/Alaskan Native	0.0%
Multiracial	10.5%
Other (please specify)	5.3%

clues peach



With which ethnic background do you most closely identify	
Answer Options	Response Percent
Hispanic/Latino	19.4%
Black	3.2%
White	58.1%
Asian/Asian American	9.7%
Pacific Islander	0.0%
Native American/American Indian/Alaskan Native	0.0%
Multiracial	12.9%
Other (please specify)	3.2%

Figure 2. The pie charts in Figure 2 indicate self reported ethnic and linguistic demographics for each treatment group

2.2. Sample

Participants (n = 122) were drawn from four-year undergraduate students in education classes, and mixed-age community college students entering an introductory astronomy class. 260 students were given the address of the survey, and asked to take it on their own time. Response rate was 47%. The ethnic and linguistic makeup of each treatment group was roughly equivalent, as shown in Figure 2. This equivalence is a result of randomization and lowers the probability of bias among the sample groups. In an attempt to limit sample bias among the entire sample, participants were recruited from both a major research University, which is majority White and English Native, and a rural community college, which is majority Latina/o and has a high percentage of English Learners. The result was a sample that more closely mirrored the demographics of California than a study that focused on only one school, especially for these two groups (Whites and Latina/os). The ethnic makeup of the entire sample is summarized in Table 2. For comparison, the ethnic makeup of California according to the 2011 census is listed in Table 3.

2.3. Measures

The treatment variable is a nominal indication of which of the three versions of CLUES a participant was shown (see Figure 1), either “Blue,” “Peach,” or “BW.” Outcome variables included nominal responses to each of the four specific visualization interpretation questions, which asked participants to indentify: (1) dark matter, (2) stars, (3) empty space, and (4) hydrogen gas (see Note-4). Each question asked participants to choose between

[4] Only dark matter and empty space were actually represented in the CLUES visualization.

Table 2. Racial/ethnic identification for the entire sample

Racial/ethnic identification	Percent of sample
Black	2
Asian	13
Multiracial	14
Hispanic/Latino	27
White	40

the structures shown in CLUES, the background, or to indicate that what was being asked about was not present in the visualization.

Finally, for ease of analysis, I created an ordinal variable summarizing each participant's responses to the visualization interpretation questions, which I called the "interpretation index." To create the interpretation index, I dichotomized participant responses to the four visualization interpretation questions as either "scientific" or "unscientific," based on their agreement with the intentions of the creators of the visualizers (i.e., structure is dark matter, background is empty space, no gas or stars visible), and summed the scientific responses for each participant. This index serves as an ordinal variable indicating roughly how well the participant has understood the visualization as a whole.

3. ANALYSIS AND RESULTS

3.1. Data Analysis

To test for independence between variables, I used Pearson's Chi-Squared test. For this test, a chi-squared probability (p) of less than or equal to 0.05 (meaning that there is a 5% chance that the relationship between categorical variables is by chance) is commonly taken as justification for rejecting the null hypothesis. Chi-squared testing was used to test the following null hypothesis: the data collected meet the distribution of a population where there is no association between CLUES version and survey responses; in other words, a participant is equally as likely to interpret the CLUES visualization scientifically regardless of the colors used in the visualization. In this case, scientific interpretation is quantified by the interpretation index, a summary variable of correct responses to four interpretation questions. Ninety one participants responded to every question in the survey and were used for the bulk of the statistical analysis. Table 4 summarizes how many participants received interpretation index scores of 0,1, 2, 3, and 4 for each of the three CLUES visualizations.

Results of chi-squared testing are summarized in Table 5. Each of the p-values in Table 5 represents the probability that the observed distribution of frequencies corresponds to a distribution that matches the null hypothesis. In other words, there is only a 0.03% chance that the higher frequency of correct responses to the question about dark matter from those who saw a visualization where the original colors were inverted is due to sampling error from a population where the frequencies are actually randomized. Thus, it can be said with confidence that the color of the CLUES visualization has an impact on learners' interpretation of dark matter in that visualization. However, the claim cannot be made that the color of the CLUES visualization has an impact on learner's interpretation of empty space in that visualization, or ability to state that hydrogen gas is not present.

Table 3. Racial/ethnic identification for the State of California. From the U.S. Department of Commerce United States Census Bureau (2011)

Racial/ethnic identification	Percent of population
Black	6.6
Asian	13.6
Multiracial	3.6
Hispanic/Latino	38.1
White	39.7

Table 4. Summary of interpretation index scores across treatment groups

Interpretation Index	0	1	2	3	4	Sum
CLUES blue	8	6	13	3	3	33
CLUES peach	3	5	6	8	6	28
CLUES BW	2	4	10	3	11	30
Sum	13	15	29	14	20	91

My results indicate that the there is a relationship between which color version of CLUES the participant viewed and how that participant interpreted the visualization. Respondents who saw the original version of CLUES ($n = 33$), which used white to indicate dark matter and blue to indicate empty space, were almost four times more likely to misidentify dark matter in the visualization than those who saw a version of CLUES where dark matter was indicated by a color that was darker than the background ($n = 58$) as shown in the pie charts in Figure 3. Chi-squared testing indicated that this result is unlikely to be by chance. Respondents who saw the original version of CLUES were also only half as likely as other participants to correctly indicate that there were no stars present in the visualization.

The interpretation index (see Section 2.3) serves as an ordinal variable indicating how well the participant has understood the visualization. Participants who saw a version of CLUES where dark matter was represented by a dark brown color were twice as likely to receive the highest interpretation score than those who saw the original visualization (CLUES blue), as shown in Figure 4. Participants who saw a version of CLUES where dark matter was represented by black on a white background were more than three times as likely to receive the highest interpretation score than those who saw the original visualization (CLUES blue), also shown in Figure 4. This relationship between the treatment group and the interpretation index was significant ($p < 0.05$).

4. IMPLICATIONS AND NEXT STEPS

The implication of these results is that the color chosen to represent various aspects of the Universe in a cosmology visualization can have an effect on learners' interpretation of that visualization. This effect is particularly strong for identification of dark matter, perhaps because learners make a rational association between the term "dark" and darker colors. Similarly, the fact that learners identified dark matter as "stars" in the CLUES Blues simulation can be attributed to a rational prior association between bright points of light and stars. Right now, visualization development that comes out of scientific research typically does not include research on interpretation, and thus decisions such as color and speed are made by scientists and artists without the benefit of learner data.

Visualizations have the potential to be a very powerful medium for presenting cosmology, a field that can seem removed from everyday experience without a visual connection to the content. But to make visualizations a more effective medium for communicating cosmology to all learners, decisions should be guided by research that includes diverse learner voices. This calls for both qualitative and quantitative research that looks at how learners use visualizations as they construct cosmology knowledge. My next step is to analyze the open-ended responses from this survey, which are rich and descriptive. In addition, I will build more quantitative experiments testing specific cues in visualizations and study qualitatively the activity of learners (Engeström 1987) as they interpret visualizations, and as they use the knowledge they constructed from those visualizations toward creating an improvable object (Wells 2002).

Table 5. Summary of calculated p-values

p-value for identifying dark matter as structure (significant)	0.000361
p-value for identifying stars as not present (significant)	0.048080143
p-value for identifying empty space as background (not significant)	0.638539422
p-value for identifying hydrogen gas as not present (not significant)	0.490919793

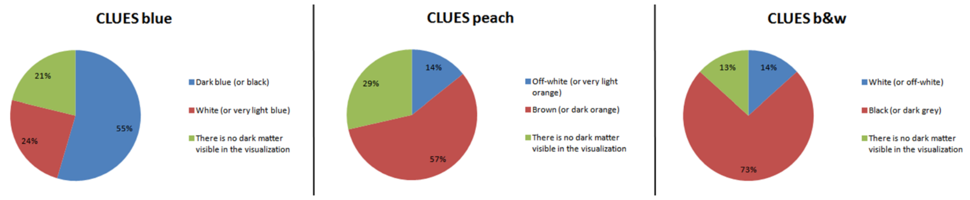


Figure 3. The pie charts in Figure 3 illustrate the colors chosen by respondents for both dark matter and stars for each CLUES sub-sample. Correct responses (in green) for each visualization for dark matter are (in order): white, brown, and black. The correct response (in green) for stars is that there are none visible. Note that the majority of participants misidentified both dark matter and stars in CLUES Blue. On the other hand, the majority of participants correctly identified both dark matter and stars in CLUES BW

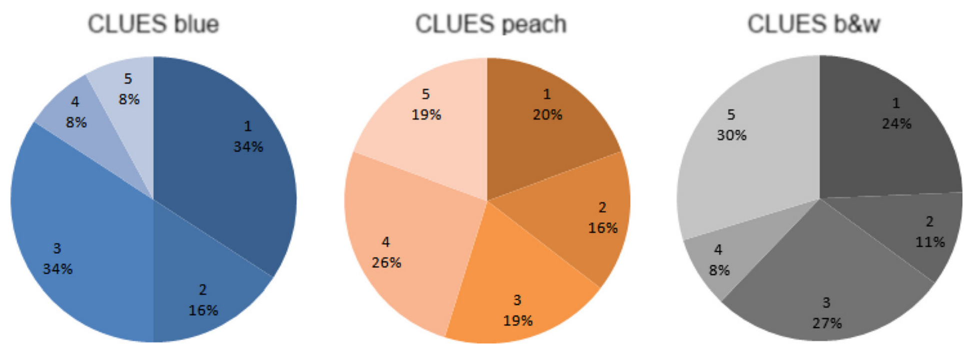


Figure 4. The pie charts in Figure 4 illustrate the interpretation indices for each treatment group (Blue, Peach, B&W). Index = 0 represents respondents who interpreted the visualization with the least accuracy, Index = 4 represents respondents who answered all four interpretation questions correctly

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Appendix: Online Survey

Before you begin, we would like you to look at short cosmology presentation. This should take less than 5 min and includes a visualization and some accompanying text. Please watch the video from start to finish and read the description below before moving on. You will not be able to return to this page once you have left.
In the visualization, starting just after the Big Band, the laws of nature are at work. The same force that keeps you grounded on Earth stops you from flying off into space, gravity, is pulling dark matter together, shaping the cosmic web, an invisible pattern that will dictate the large-scale structure of the galaxy distribution. This is the spine of our universe. Starting from random ripples, Dark Matter and Dark Energy are shaping the cosmic backbone. Over billions of years, dark matter is pulled into immense, massive filaments, strengthening the web.
Smaller clumps of Dark Matter are formed as well, and inside of these, although we cannot see them here, galaxies form.

In the visualization, we first see the formation and evolution of the cosmic web. Then, we travel through this invisible cosmic web, toward the Virgo Supercluster, home to our Milky Way Galaxy.

1. What answer best describes your gender?

- Male
- Female
- Intersex
- Questioning

2. Please choose the answer that best describes your education level.

- I have not graduated from high school or the equivalent.
- I have a high school degree or equivalent.
- I am currently in a 2 year associates degree program, or 2 year transfer program.
- I am currently in a 4 year bachelors degree program.
- I hold a bachelors degree.
- I hold one or more doctoral degrees (MA, PhD, EdD, etc)

3. Is English your first language?

- Yes.
- No.

4. With which ethnic background do you most closely identify (you may check more than one answer if it applies):

- Hispanic/Latino
- Black
- White
- Asian/Asian American
- Pacific Islander
- Native American/American Indian/Alaskan Native
- Multiracial
- Other (please specify)

5. Have you ever been diagnosed as color blind, or do you suspect yourself to be colorblind?

- Yes
- No

6. How likely are you to read about, watch or listen to astronomy content outside of what is required for school?

- Very likely.
- Somewhat likely.
- Not very likely.
- Not at all likely.

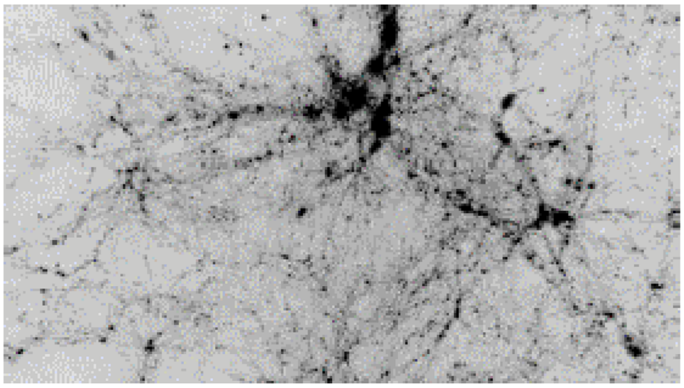
7. Please answer the following questions as best you can, or mark "I have no idea."

	Yes.	No.	I have no idea.
Most plants get their energy from the Sun.			
Jupiter is the largest planet in our Solar System.			
Lithium is the lightest element in the periodic table.			
An object's gravity is determined by its mass.			
Our Sun is the largest star in the galaxy.			
An object's acceleration is always equal to its speed at any given moment.			

8. Did the visualization in the cosmology presentation look familiar to you?

- Yes.
- No.

The following image is a still frame taken from the visualization in the cosmology presentation, provided for reference.



9. Please describe what you saw in the cosmology presentation.

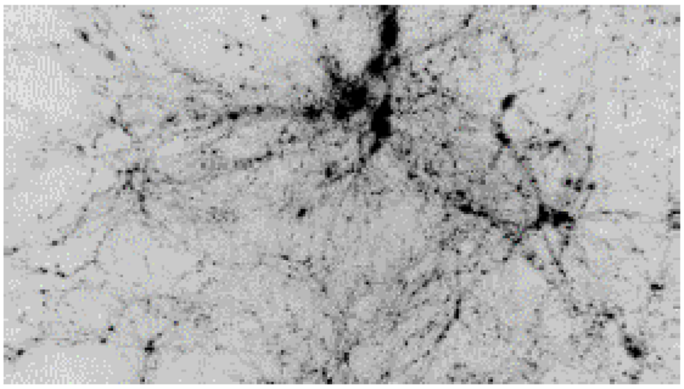
10. What part of the Universe was being depicted in the cosmology presentation?

11. When did the events shown in the visualization in the cosmology presentation take place? Please choose the best answer.

- In the moments immediately after the big bang.
- Continuously from the moments immediately after the big bang until the present day.
- Within the last million years.
- They have not taken place yet.

12. How is gravity involved in the events shown in the visualization in the cosmology presentation?

The following image is a still frame taken from the visualization in the cosmology presentation, provided for reference.



13. Using what you remember from the cosmology presentation, what color is the dark matter in the image above?

- Black (or dark grey)
- White (or off-white)
- There is no dark matter visible in the visualization.

14. Using what you remember from the cosmology presentation, what color are the stars in the image above?

- Black (or dark grey)
- White (or off-white)
- There are no stars visible in the visualization.

15. Using what you remember from the cosmology presentation, what color is the empty space in the image above?

- Black (or dark grey)
- White (or off-white)
- There is no empty space visible in the visualization.

16. Using what you remember from the cosmology presentation, what color is the hydrogen gas in the image above?

- Black (or dark grey)
- White (or off-white)
- There is no hydrogen gas visible in the visualization.

17. What resources did you draw on the most to answer the questions about the visualization in the cosmology presentation?

- The text that accompanied the video
- My own previous knowledge about cosmology
- Both the text that accompanied the video, AND my own previous knowledge about cosmology
- I just guessed

18. Was there anything in the visualization that confused you? If so, what?

19. Do you have any additional comments about the visualization in the cosmology presentation? If so, please share them here.

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