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RESEARCH REPORT

Developing Effective STEM Animations: Application of a Multimedia Learning Theoretical Framework

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Abstract: *Although most people believe animations can be very effective for STEM instruction and engagement, research often leads to findings that they are not superior to static graphics or other information presentations. The reason for these failures is not inherent in animations. Rather, the failures often reflect non-adherence to principles of good graphics design and a lack of understanding of principles of STEM learning. Sci-Toons, a series of animations dealing with diverse STEM topics, were developed based on a theoretical learning framework and the use of teams comprised of individuals with scientific expertise and individuals with visual design expertise. The process employed in the development of these animations is presented along with data on the wide-spread dissemination of Sci-Toons, its impacts on viewers, and its impacts on students involved in their production.*

Keywords: STEM Education, informal education, animations, videos, narratives, framework.

The need to produce more STEM graduates to maintain the national security and economic future of United States is well established (U.S. Office of Science and Technology Policy, 2012; U.S. Department of Commerce, 2012), as is the need to develop comprehensive strategies to increase the numbers of students in STEM pipelines and retain interested STEM students until graduation (Cohoon & Chen, 2003; Seymour & Hewitt, 1997; Zweben & Bizot, 2012). Women and underrepresented minorities, who now make up approximately 70% of all college undergraduates in the U.S., are historically underrepresented in STEM programs (National Science Foundation, 2013). A more diverse STEM workforce makes better use of our country's human resources and leads to more diverse points of view and more effective problem solving (Margolis, Estrella, Goode, Holme, & Nao, 2008; Melguizo & Wolniak, 2012; Page, 2007; Perna et al., 2009).

Approaches for diversifying and increasing the number of individuals entering universities to obtain STEM degrees include successful combinations of in-school and out-of-school STEM intervention programs that engage students from all backgrounds (Adetunji et al., 2012; Falk & Dierking, 2010; U.S. Office of Science and Technology Policy, 2010). Numerous reports also suggest that informal learning environments can strengthen science interest and aptitude on a national scale (National Governors Association, 2012; National Science Board, 2007; U.S. Department of Education, 2007).

One approach that most people believe can be very effective in engaging students from all backgrounds and stimulating interest in an area is the use of animations. Animations should be effective in portraying changes over time; they should be effective and engaging learning and teaching tools. However, research often leads to the findings that animations are not superior to static graphics or other presentations of information (Karlsson

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& Ivarsson, 2008; Kim, Yoon, Whang, Tversky, & Morrsion, 2007; Tversky, Heiser, & Morrison, 2013; Tversky, Morrison, & Betrancourt, 2002). The reasons for these failures is not inherent in animations. Rather, failures often reflect violations of cognitive principles of good graphics design.

According to the Congruence Principle, there should be a correspondence between the concepts portrayed and the information to be conveyed (Tversky, Heiser, & Morrison, 2013). For example, building a LEGO object is a continuous process. However, people think of the process as a series of discrete steps. Accordingly, LEGO instructions portray these steps -- and also change scale, size, and even perspective to more clearly map the task to the way the user thinks (Tversky et al., 2006). Similarly, people think of geographic travel in terms of turns at specific points. The classic map of the London Underground, designed in 1933, reflected this and emphasized the important information (the sequence of subway stops) and de-emphasized the unimportant information (distance and deviations from a straight line) (Agrawala, Li, & Berthouzoz, 2011).

Another cognitive design principle, the Apprehension Principle, states the importance of accurately perceiving and conceiving animations. The animations must be slow enough and clear enough to allow viewers to see and understand the concept being conveyed (Tversky, Morrison, & Betrancourt, 2002).

The Cognitive Theory of Multimedia Learning (CTML) provides guidelines for designing animations, based on cognitive principles (Mayer, 2005). Words and images are processed differently in the limited space comprising each channel's working memory. Each provides its own, separate contribution towards the creation of a mental model. An effective animation must recognize the cognitive load it creates and optimize the balance induced by different types of cognitive demand (called essential processing, extraneous processing, and generative processing).

Essential processing represents provision of the information necessary for understanding the constructs being demonstrated. Operationally, this can be accomplished through application of the pretraining principle (providing information before the animation, as through a glossary of terms) and the modality principle (presenting words aurally rather than visually). Extraneous processing can be reduced through adherence to the coherence principle (presenting only relevant aural and visual information; eliminating unnecessary distraction), the redundancy principle (avoiding narration that merely repeats prose presented visually); the signaling principle (providing a "road map" to delineate the organization of the material prior to presenting the material); the temporal contiguity principle (synchronizing narration with visual presentations); and the spatial contiguity principle (placing labels proximal to the elements they represent). Generative processing can be facilitated through application of the interactivity principle (providing opportunities for viewers to control elements of the animation) (Yue, Kim, Ogawa, Stark, & Kim, 2013).

Using the above principle, Yue et al., (2013) rated 860 randomly selected medical animations. Most employed at least one of these principles, but certain principles were rarely employed. Only 8% provided key terms prior to the animation; 17% used narration to enhance visual presentation, and only 19% employed the signaling principle. Conversely, nearly all (92%) placed labels proximal to images. The authors also pointed out the substantial influence of experts on the animations and the likelihood that things which are "intuitive" to the expert may not be knowledge possessed by novices, leading to the omission of steps crucial for a novice's understanding.

The process of creating animations can have strong and positive impacts on the animators as well as the audience. DiBlas, Paolini, & Sabiscu (2010) surveyed 153 kindergarten and primary school teachers who employed digital storytelling as a classroom activity about this practice's educational benefits. In comparison with "regular teaching", over 95% of these teachers felt student achievement was either "better" or "much better" with respect to interest in a subject matter, engagement, and deep understanding. Between 90 - 95% of the teachers noted improvement with respect to content organization skills, retention, technical abilities, communication abilities, and teamwork capacities. Prakash et al. (2009), working with a group of predominantly Native American and Alaska native elementary school children, demonstrated digital storytelling as an effective tool for engaging underrepresented minority students in science. And, Xu, Park, & Baek (2011) showed digital storytelling can be employed in virtual learning environments to enhance college students' writing self-efficacy.

Building on these principles and guidelines, the Multimedia Learning Theoretical Framework (MLTF) was developed. It begins with a model of the audience (Audience Pipeline Structure) to identify the ways to present information (stories) for the desired audience.

The Multimedia Learning Theoretical Framework (MLTF)

The MLTF is composed of three elements: (I) Audience Pipeline Structure, (II) Multimedia Learning Medium, and (III) Multimedia Learning Products. These are discussed below.

The Audience Pipeline Structure: STEM Literacy

The audience pipeline structure is an element of the MLTF that focuses on understanding the background of problem solvers, their preferred approach to problem solving and the development of a mechanism for engaging them in the learning process. Cognitive and neuroscientists have argued that there are different modes of thinking (Bruner, 1986; Gazzaniga, 2005; Kahneman 2003; Kahneman, 2011; Sperry, 1961). Bruner, for example, argues that there are two ways of thinking: a paradigmatic (logico-scientific) mode and a narrative mode. Figure 1 is a schematic diagram of the Audience Pipeline Structure, incorporating these different problem-solving approaches.

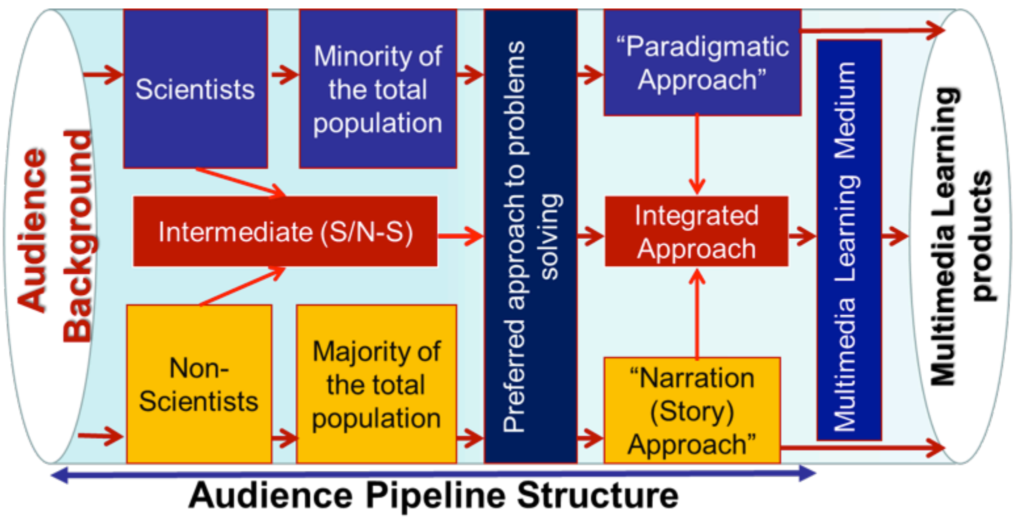

Figure 1. *Multimedia Learning Theoretical Framework (Model)*

A simple division of the audiences into scientists and non-scientists does not take into account the potential diversity of thinking styles within disciplines or the fact that a single individual can have varying roles, approaches, and levels of expertise in different contexts. This Audience Pipeline Structure makes room for an intermediate audience between scientists and non-scientists, explicitly recognizing a variety of problem-solving styles and experiences. An intermediate audience approach to problem solving is dubbed an integrated mode or approach. The integrated approach combines both the narrative and paradigmatic modes to accommodate broad thinking styles, accessible by a wide range of audiences from diverse backgrounds.

For example, a narrative approach video on "Climate Change" would be comprised of stories and pictures of the impacts of climate change along with stories and pictures of fossil fuel power-generating plants and automobiles spewing greenhouse gases into the atmosphere. A similar video, using the paradigmatic approach, would provide graphic data on climate characteristics (such as temperature and precipitation) and potential climate forcing mechanisms (such as atmospheric carbon dioxide concentrations, solar radiation, volcanism, orbital variations, etc.) over time. An intermediate approach would tell a story (or set of stories), presenting the underlying hypotheses and data (as appropriate), using pictures, videos, and other graphics.

Multimedia Learning Medium

Multimedia allows both learners and experts to construct a coherent integrated representation of a domain content's narrative, visual and verbal representations. This medium also allows smooth integration of the Audience Pipeline Structure with research on multimedia, such as instructional methods in which visuals are added to a verbal explanation so as to foster deeper understanding when learners mentally connect the verbal and pictorial representations (Mayer, 2005; Yue, Kim, Ogawa, Stark, & Kim, 2013). Animations are developed and produced by Sci-Toon Creation Group (SCG) members who learn about (and employ) design principles and issues important in the design of multimedia (dual channels, limited capacity and active learning) and evidence-based principles for the design of multimedia learning environments (Mayer, 2008; Tversky, Heiser & Morrison, 2013).

Multimedia Learning Products

This component of the Multimedia Learning Theoretical Framework is designed to convert the developed domain content narratives to storyboard and final multimedia products. Media such as animation, artistic renderings and/or video creations are used to develop multimedia learning products for engaging broad audiences in science.

Application of Multimedia Learning Theoretical Framework

Sci-Toons targets an intermediate audience. Accordingly, the Sci-Toon Creation Group (SCG) is also "intermediate", meaning it is composed of experts and novices in STEM fields. In other words, the composition of a SCG includes at least one STEM major, one faculty member and two non-STEM majors. The SCG used the MLTF's integrated approach for problem solving through interactive engagement by SCG members and included iterative feedback on Sci-Toon scripts and storyboards. The iterative feedback mechanism allows domain STEM content experts and novices who are members of the SCG to provide constant feedback during each step of the Sci-Toon development (script, storyboards and final animations). As the script is being developed, the STEM domain expert(s) contributes to the script by overseeing the overall accuracy of the scientific content. As the script undergoes iterative reviews, the narrative aspect of the integrated approach is in focus. Thus, the final script and storyboards incorporate the paradigmatic and narrative contributions from STEM experts and non-STEM expert/novices. See Figure 2 below.

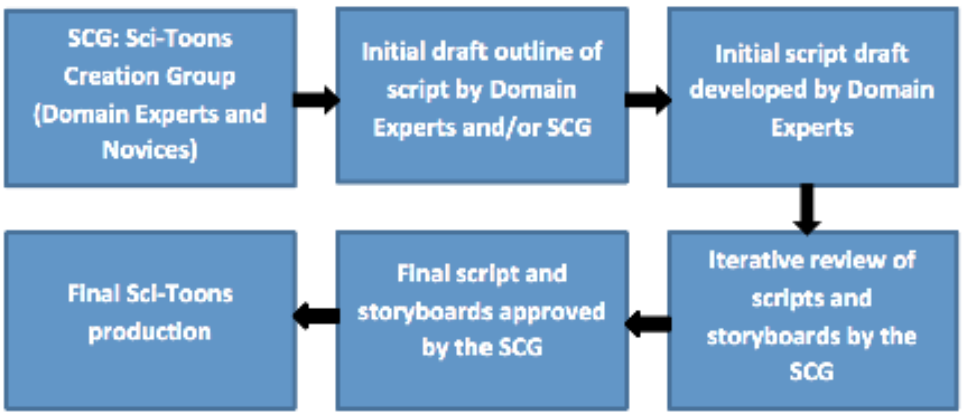

Figure 2. *Diagram of the Sci-Toon Creation Process*

This integrated approach is unique among existing online resources because it harnesses the contribution of individuals from a wide range of backgrounds in development of a final product. Table 1 shows how Sci-Toons differs from the ways other online resources are developed.

Table 1:
Sci-Toons versus Other Online Resources

Other Resources: EdX, Khan Academy, One-Minute Physics and MOOCs	Sci-Toons
Developed using paradigmatic approach	Developed using narrative or integration approach
Developed by domain content experts	Developed by domain content experts and novices
Might contain significant technical jargon	Technical jargon is limited
Emphasis is on getting the domain content right	Emphasis is on getting both domain content right and language at the level of the target audience
Content scripts are reviewed only by domain experts	Content scripts are reviewed by both domain experts and novices

The Sci-Toons model for learning (Adetunji, 2015) starts with concepts familiar and important to the SCG members and then gradually introduces more advanced scientific concepts through script development, storyboard creation and visual media. SCG members expand their understanding of scientific concepts or scientific research by examining content domain and creating stories that they animate. They learn as they explore, script, storyboard, and animate their chosen topic: non-STEM experts learn the science while STEM experts learn how to explain. Viewers (the target audience) expand their understanding of scientific concepts by following the explanations of new learners – that is, the new learners that make up the SCG.

Science Cartoon (Sci-Toon) Projects

The application of MLTF to each of the three key steps (scripting, storyboarding, and producing the animation) to Sci-Toons video development begins with selection of the SCG members. There is diversity in their academic backgrounds: A typical SCG includes STEM and non-STEM students and faculty. The SCG members begin by deciding on an area of scientific research or on a concept that the group will explore. Then, a subset of the group is charged with the development of the initial script based on this topic. The initial draft is then reviewed by the entire group. Each SCG member brings his or her unique perspective and provides feedback on the script, which goes through several iterations of reviews and edits before it is finalized. A finalized script usually has a theme and a hook (that is, something to capture or maintain the audience's interest) for the story. The script is written in language that a broad audience can understand while keeping the core of the scientific research or concept accurate.

In all of the key steps of Sci-Toon development, the SCG members focus on developing materials for an intermediate audience. This is facilitated by the SCG's diverse problem-solving styles and experiences. In addition, Sci-Toon development employs the intermediate audience's preferred approach to problem solving by incorporating both paradigmatic and narrative approaches. A description of how MLTF was applied for the production of three different Sci-Toon videos is described below.

Weather and Climate (https://www.youtube.com/watch?v=UC38Rf70px8)

During the initial meeting, when the SCG members decided to pick Weather and Climate as a topic, it was clear that time scale was an important distinguishing factor. Meteorologists focus on a very short time scale compared with the much longer time scales of interest to climatologists. The SCG developed a hook for the body of the story: When going on vacation, check the climate to decide what to pack and check the weather to decide what you should be wearing when you arrive.

The main points of the story evolve around what Meteorology and Climatology are and how they are different. For Meteorology, tools such as thermometers, barometers and anemometers are used to collect temperature, air pressure and wind speed data. These atmospheric data conditions are gathered into supercomputers that use forecasting models to predict conditions in the near future. The representations use "numerical forecast equations" to create models of the atmosphere. Meteorologists take into consideration previous weather patterns and knowledge of how the different aspects of the atmosphere interact with each other and can be used to predict weather patterns, though only for a short period into the future. The farther into the future, the greater chance of error in the prediction. In contrast, climatologists study weather systems long term, over years or millennia, tracking trends and changes over time and predicting averages and changes in atmospheric conditions over years. Both Meteorology and Climatology use radar, satellite data, and sophisticated computer models for weather forecasting or climate models predictions.

In order to demonstrate the iterative nature of script development, we used text visualization software (McNaught & Lam, 2010) to enable comparisons of initial and final versions of scripts. Word visualization software displays the frequency with which different words appear in a document (ignoring common words, such as "the", "an", "on", etc.) by increasing the size of a word in proportion to its occurrence. The following figure, showing word clouds for the initial and final scripts used for Sci-Toons were produced using TagCrowd (TagCrowd, 2015).

Figure 3. *Visualization of the top 50 words of the initial Weather and Climate script (left) and of the top 50 words of the final script (right)*

In the initial Climate and Weather Sci-Toon, the most frequent word was "change", appearing 23 times. Four of these uses were in the context of "climate change", reflecting the content experts' desire to incorporate this important, but extraneous, concept in the video. However, in the final script, the word "change" was not among the 50 most common words and the phrase "climate change" did not appear. Terms such as models, planning, predictions, atmosphere, and forecasting increased dramatically in their prevalence, reflecting the increased focus on these terms and concepts for telling a story in the final version. (See Figure 3.)

How Do We See Color? (https://www.youtube.com/watch?v=pvC9MQvqHMQ)

The initial topic for this Sci-Toon was color. It quickly became clear that color is a broad topic that cuts across multiple disciplines including physics, chemistry, neuroscience, and the visual arts. Each of these fields has contributed to the understanding of color from different perspectives. The SCG finally decided to focus on how color is perceived. Their hook focused on the different ways in which color is used: Artists use different colors to express emotion, marketers attach colors to their brands to make them more recognizable and animals use colors to try to avoid predation.

Color was defined as the limited range of light that humans can see, which, in turn, introduced the concept that color was based on the wavelength of light reflected by an object. The Sci-Toon then focused on how visible color or light is perceived by our eyes and the role of different parts of the eyes including the cornea, pupil, retina, ganglion cells and the light sensitive cells known as rods and cones. Rods are responsible for our perception of light and dark and our peripheral vision. Cones allow us to see color. They are found in the center of the retina, where light is focused. In humans, cones come in three varieties, each sensitive to a different range of light.

The final part of the story focused on other animals' perception of color. Animals have different kinds and number of cones, which allow them to see the world differently from humans. Dogs are more limited in the wavelengths they can see because they only have two types of cones, leaving them "colorblind" to differences between red and green. Butterflies have four types of cones in their eyes, letting them see ultraviolet light. The animal with the best color vision might be the mantis shrimp, which has 12 different kinds of cones.

The evolution of the Sci-Toon, from initial script to final script, is presented as a word cloud (Figure 4). One can see the decreased prevalence of terms relating to the physical properties and characteristics of light (reflectance, newton, prism) that characterized content experts' classical presentations of color and the increased prevalence of certain words, such as cells, cones, retina, and rods in the final How Do We See Color? Sci-Toon, reflecting the increased importance of biological concepts in the story being told.

Figure 4. *Visualization of the top 50 words of the initial How do we see color? script (left) and of the top 50 words of the final script (right)*

The Conductive Polymer (https://www.youtube.com/watch?v=UjMbwS0LOkU)

The goal of this Sci-Toon was very clear from the onset. The SCG wanted to develop a script about the discovery of conductive polymers that would be very engaging to any audience. The initial script started with a description of electric current and its usage in everyday gadgets such as mobile phones, tablets and laptop computers. The script continued with the history of the accidental discovery of a polymer, polyacetylene, which exhibited metallic properties and the mechanism by which this polymer conducts electricity. As the initial script was being revised by the SCG members, there was a general consensus that it lacked a compelling hook. It was decided that the fact that certain non-metallic objects, such as some plastics, could be good conductors of electricity would be surprising and engaging to the audience and would serve as the hook.

Figure 5 shows the evolution of the Conductive Polymer script. In contrast to the other word clouds presented, the basic theme and presentation in the initial and final scripts were quite similar. Unlike the production of the other Sci-Toons, the SCG members working on the project discussed the project extensively, clearly articulating the goal and concepts to be covered before beginning to write the initial script. The Conductive Polymer script was finalized after the second iteration of reviews. A slightly different process was employed for the other two Sci-Toons, for which the SCG members initially chose the topic and then designated

1-2 members to write an initial draft. The drafts were then reviewed and edited by the all participating SCG member and went through at least five iterations of reviews before the script was finalized.

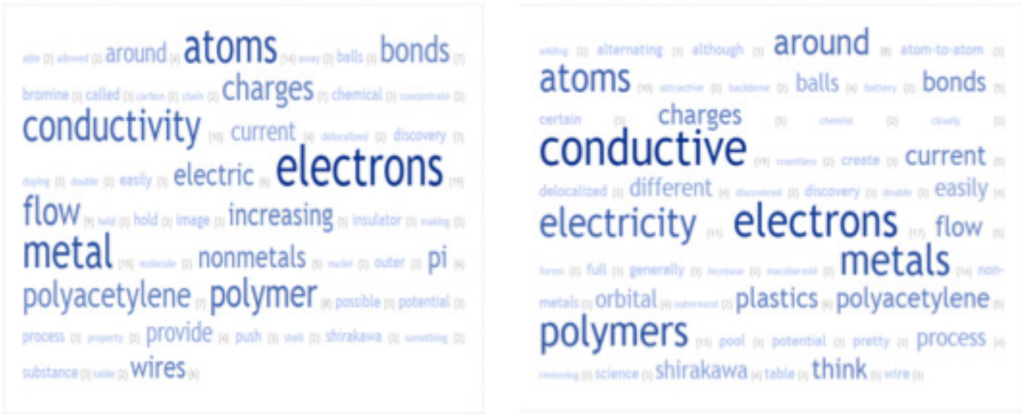

Figure 5. *Visualization of the top 50 words of the initial Conductive Polymer script (left) and of the top 50 words of the final script (right)*

Methodology

Viewers' demographics were measured through use of Google Analytics (www.google.com/ analytics/), based on information gathered from logged-in users on all electronic devices.

In order to assess the impacts of participation in a SCG on college students, a brief, five-minute electronic survey was developed and emailed in December, 2014, to all 23 students who had been involved with Sci-Toons prior to the Fall 2014 semester. A copy of the survey is included as Appendix 1. Two reminder emails were sent to non-respondents, two and four weeks after initial survey distribution. Completed surveys were received from 10 of the respondents, for a response rate of 43%. The survey and data collection procedures were determined to be exempt from a need for review by Brown University's Institutional Review Board. Informed consent was obtained from all individual participants included in the study.

Impacts of viewing the Conductive Polymer video were assessed through a brief survey of students participating in the Brown Science Prep (BSP) Program. BSP is designed to engage public high school students in science. Students come to Brown on a weekly basis to do science experiments and demonstration-based lessons in an informal environment. Thirty-four students viewed the video and completed a voluntary electronic survey after viewing the Sci-Toon.

Results

We begin by providing demographic data about individuals downloading Sci-Toons videos and information about average view times. These are followed by data provided by college students who were part of the Sci-Toons creation groups (SCG) and who responded to our survey. They were involved in the production of between one to four different Sci-Toons. Finally, data provided by high schools students who viewed the Conductive Polymer Sci-Toon are presented.

Viewer demographic and download data

All the three Sci-Toons described in this paper have been viewed multiple times and downloaded in many different countries. Table 2 shows the view counts and the number of countries where the videos have been downloaded since they were uploaded (publication date) to the Sci-Toon YouTube Channel. To our surprise, in a 13-day period, from May 19, 2015 to May 31, 2015, the Color Sci-Toon video went viral: the number of downloads increased by 45,888 (from 8,761 to 54,649). Over the same period, the number of downloads of the Conductive Polymer Sci-Toon only increased by 430 (from 7,253 to 7,683).

Table 2.
View counts and Number of Countries where the Conductive Polymer, Color, and Climate and Weather Sci-Toons have been viewed (as of May 31, 2015)

Sci-Toon	Publication Date	Number of Views	Number of Countries
Conductive Polymer	October, 2013	7,683	109
Color	April, 2014	54,649	179
Climate and Weather	January, 2015	347	27

Demographics of viewers of the Conductive Polymers, the Color, and the Weather and Climate Sci-Toons are presented in Figures 6 -8. Overall, the majority of the Conductive Polymer Sci-Toon were male (75.5% male vs. 24.5% female); nearly half (47.1%) were between 13 -24 years of age). The Color Sci-Toon was more likely to be viewed by females than males (38.1% vs 61.9%, respectively). The Color Sci-Toon viewers were also younger, with 62.2% between 13 - 24 years old and 37.8% aged 25 years or older. The Weather and Climate viewers were equally likely to be female (51.6%) or male (48.4%). Like the Conductive Polymers viewers, about half (51.6%) were between 13 - 24 years of age.

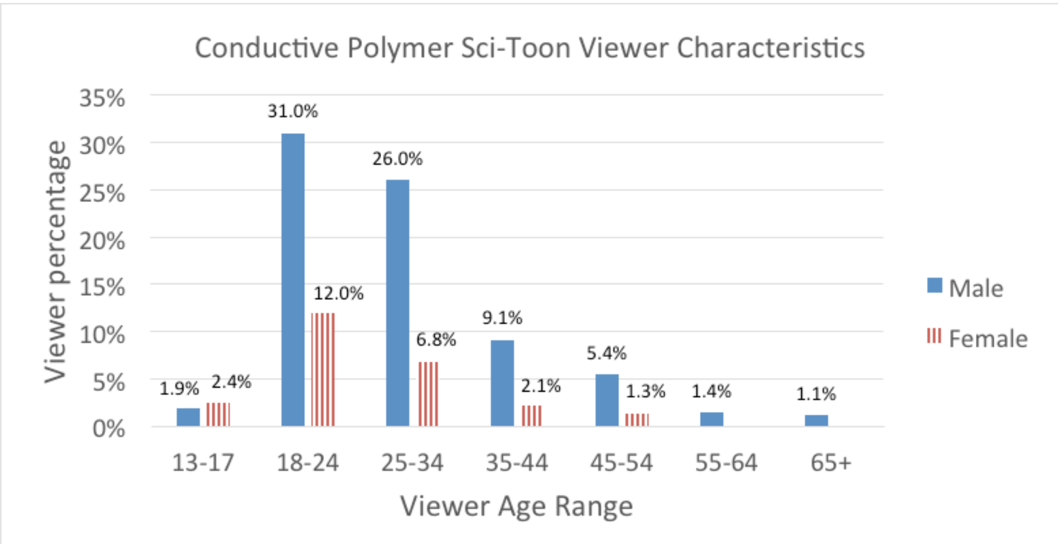

Figure 6. *Age Range and Gender of Conductive Polymer Sci-Toon viewers*

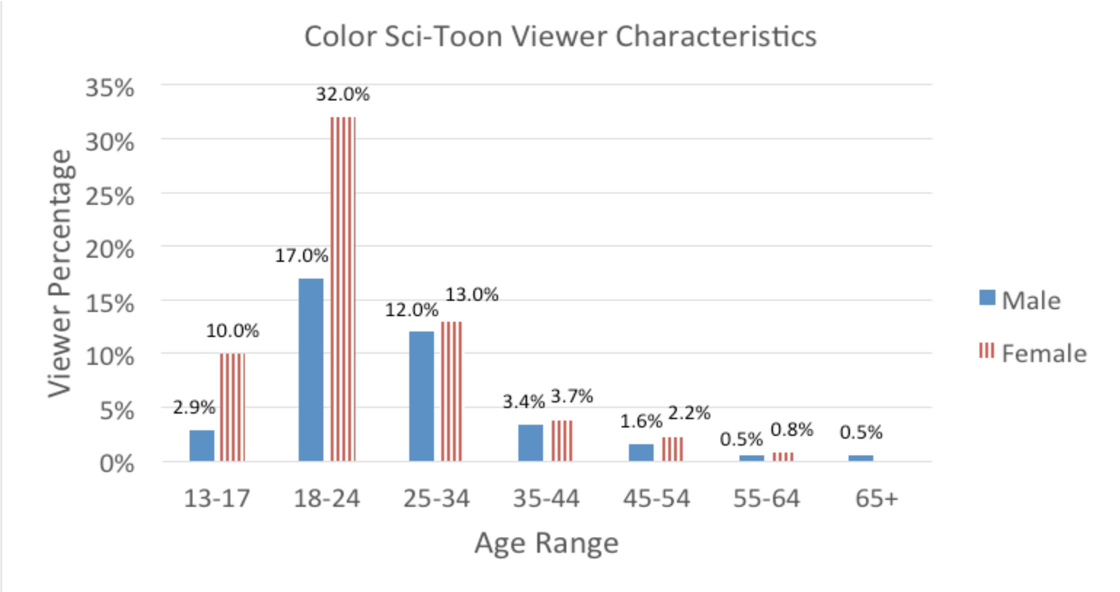

Figure 7. *Age Range and Gender of Color Sci-Toon viewers*

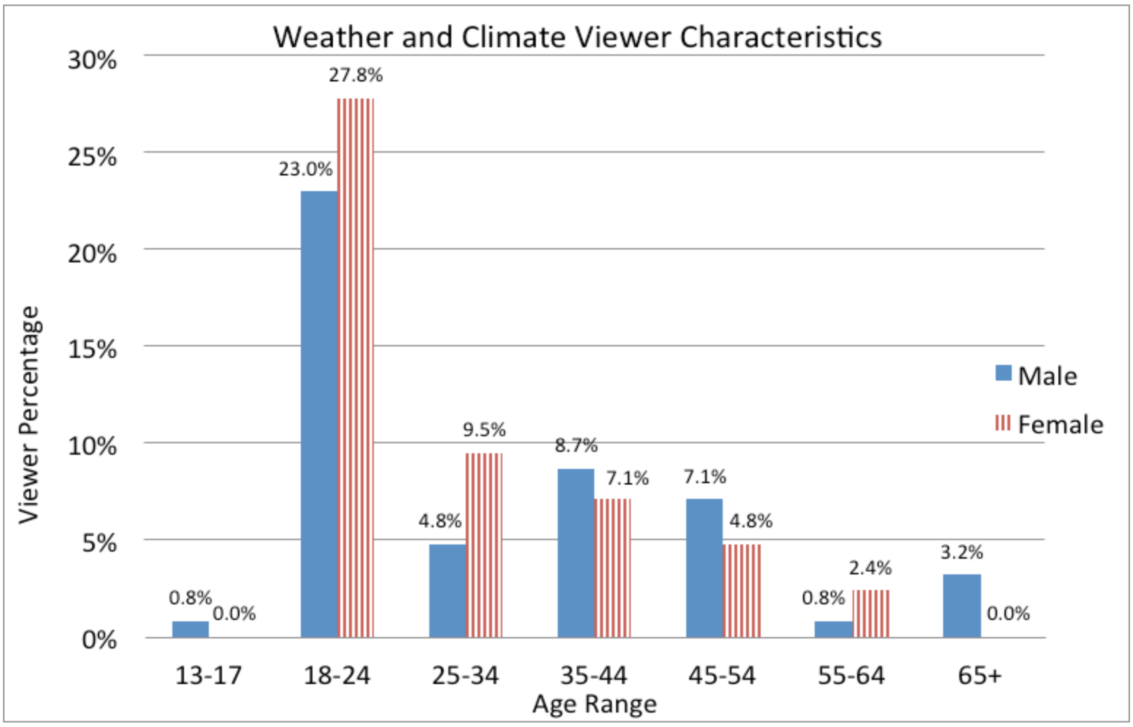

Figure 8. *Age Range and Gender of Weather and Climate Sci-Toon viewers*

The viewer demographic data do not necessarily reflect the numbers of individuals viewing a complete Sci-Toon. Some viewers may download the video and view later; others will watch and log off before the end of the video. For example, the Conductive Polymer Sci-Toon had an average viewing time was 3.49 minutes -- or about 57% of the length of the Sci-Toon.

Viewer demographic and download data

The survey completed by students who were SCG members included items asking them to evaluate how their participation in the Sci-Toons project affected their abilities to understand contemporary science issues and to explain scientific principles and issues to others. All of the students indicated positive changes, with the majority of respondents indicating these abilities were moderately improved. (See Figure 9.)

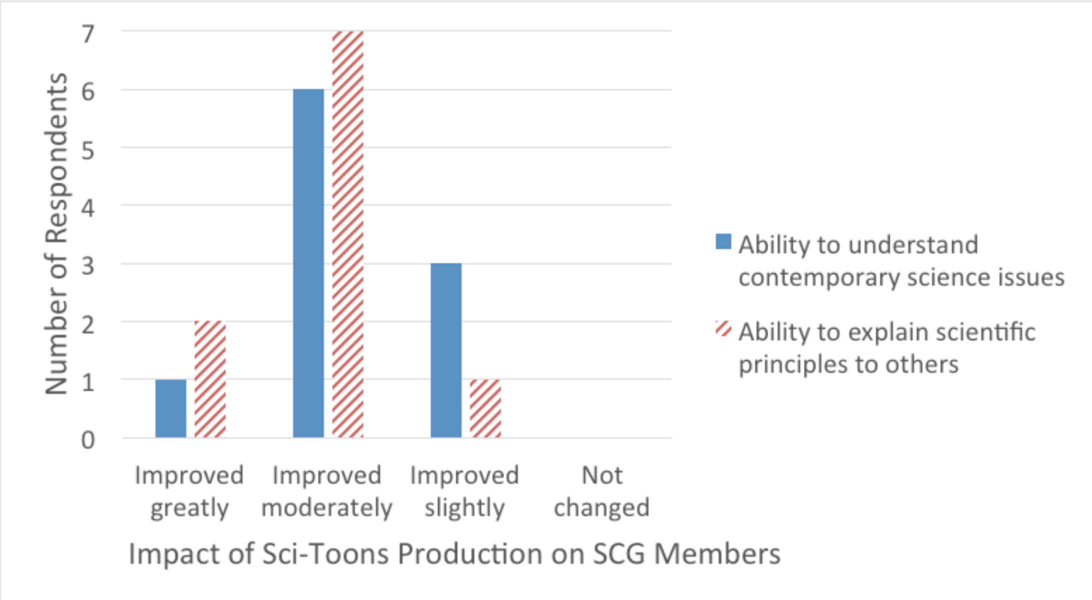

Figure 9. *Self-assessed Impacts of Participation in SCGs on College Students*

Respondents were also asked how important they felt it was for the general public to understand science and how difficult it was for the general public to understand science, both before and after their Sci-Toons experience. Overall, respondents reported non-statistically significant increases in the importance of the public understanding science and decreases in the public's perceived difficulty in understanding science. See Table 3.

Table 3.
Self-reported Changes in SCG College Students' Attitudes about Public Science Understanding

Item	Before	After	Change
How important is it for the general public to be able to understand science*	3.80	4.30	+0.50
How difficult is it for the general public to understand science**	2.56	3.00	+0.44

*: Not important=1; Slightly important=2; Moderately important=3; Very important=4; Extremely important=5.
**: Extremely difficult=1; Very difficult=2; Moderately difficult=3; Moderately easy=4; Very easy=5; Extremely easy=6.

Half of the respondents were science majors; half were not. All of the non-science major respondents reported that their Sci-Toons experience either slightly or moderately increased their likelihood of pursuing a STEM-related career. All of the science majors reported no change in the likelihood of their pursuit of a STEM-related career.

Impacts on Viewers

Thirty-four students participating in the Brown Science Prep Program viewed the Conductive Polymers Sci-Toon and completed a brief, voluntary survey afterwards. This survey included items asking students to indicate their level of agreement with various statements about the Sci-Toon.

Results are presented in Table 4. A large majority of the students indicated they felt the Sci-Toon was interesting (94.1%) and easy to understand (88.2%). Most also felt that they learned a lot (88.2%) and that watching the Sci-Toon was a good use of their time (88.2%). Nearly all would recommend it to friends who like science (94.1%). However, less than half would recommend it to friends who do not like science (44.1%).

Table 4.
Agreement with Statements about the Conductive Polymer Sci-Toon by High School Students

	Rating*	% Agreement**
I would recommend watching Sci-Toons to friends who like science	3.21	94.1%
The Sci-Toon was interesting	3.12	94.1%
I learned a lot from the Sci-Toon	3.06	88.2%
The Sci-Toon was easy to understand	3.00	85.3%
Watching the Sci-Toon was a good use of my time	2.97	88.2%
I would recommend watching Sci-Toons to friends who do not like science	2.35	44.1%

*: 1 = Strongly disagree; 2 = Disagree; 3 = Agree; 4 = Strongly agree
**: Percentage of students either agreeing or strongly agreeing with the statement.

Discussion

The Multimedia Learning Theoretical Framework (MLTF) model can easily be adopted for use in both formal and informal academic settings. As an experimental approach to teaching and learning, it allows both STEM and non-STEM learners along with experts to work together as domain concepts are being presented. The process is intended to expand understanding of the domain concept for both the learners and the experts as they engage in the iterative process of script development. The experts are exposed to a new way of thinking about the domain concepts as they work in collaboration with the learners within the integrated approach of the MLTF's Audience pipeline structure.

Tversky et al. (2006) noted the need for collaboration between graphic designers and domain experts in order to create effective visualizations. They also noted the practical difficulties of such collaborations. The MLTF model was applied as the basis of Sci-Toons to help overcome these difficulties and the problems that have prevented animations from reaching their potential as tools for STEM education and approaches for engaging students and the general public with STEM. This model accommodates broad thinking styles, accessible by a wide range of audiences from diverse backgrounds. It is applicable to secondary, intermediate school, and even primary school students, for whom digital story-telling has been shown to be an effective means of engaging children with science (DiBlas, Paolin, & Sabiescu, 2010; Prakash et al., 2009).

The prevalence of downloads is suggestive of wide use. In addition, the demographics of downloaders suggest different audiences are being reached by the different Sci-Toons. The Color Sci-Toon was more likely to be viewed by females; the Conductive Polymers Sci-Toons, more likely to be downloaded by males. Assuming that the 13 - 17 years olds are primarily secondary school students, about 4% of the Conductive Polymer Sci-Toon viewers and 13% of the Color Sci-Toon viewers were secondary school students. Similarly, it is reasonable to assume that post-secondary students make up a substantial proportion of the 18 - 24 year olds, who comprised 43% of the Conductive Polymer Sci-Toon, 49% of the Color Sci-Toon, and 51% of the Weather and Climate Sci-Toon viewers.

We can only speculate on reasons that the Color Sci-Toon's popularity skyrocketed in the last half of May, 2015. These increases occurred across all age categories but were most pronounced among the younger viewers (an eight-fold increase for 13 - 17 year olds and nearly a ten-fold increase for 18 - 24 year olds). Overall, male viewers increased by a factor of 4.5; female viewers increased by a factor of 7.6. The Sci-Toons were roughly of comparable length. Viewing time for the Climate Sci-Toon is 3 minutes, 56 seconds; for the Color Sci-Toon, 4 minutes, 3 seconds; and for the Conductive Polymer Sci-Toon, 6 minutes, 4 seconds. We noticed that the Color Sci-Toon, which is formally listed as How Do We See Color?, is the only Sci-Toon of the eight that have been published whose title is a question. Perhaps individuals who choose questions as search terms would be more likely to find and download a video with a matching title -- but this does not necessarily explain the sudden increase in popularity.

Impacts were assessed through a survey of students directly involved with the production of Sci-Toons. We feel post-participation surveys provided suggestive evidence of impacts, particularly on attitudes towards STEM and STEM careers for non-STEM majors. We anticipate administering pre- and post-participation surveys to provide stronger evidence of positive impacts. For assessing impacts on viewers, data from a survey of high school students were positive. Their agreement with a statement that they learned a lot from the Sci-Toon is suggestive of the animation's positive impact on learning. However, metacognitive judgments of learning are weak indicators of learning (Jaeger & Wiley, 2014; Paik & Schraw, 2013; Thiede et al., 2010; Yue, Bjork, & Bjork, 2013). These students, by virtue of their choice to participate in a voluntary science program, were almost certainly positively predisposed to the sciences before viewing the video and represent one of the important target audiences for Sci-Toons. In addition, a small number of viewers of the on-line videos provided optional comments which were nearly all positive, with several posing intriguing technical questions and requesting further information.

The underlying goals of Sci-Toons are to improve STEM education and stimulate interest in STEM. The Committee on STEM Education of the National Science and Technology Council recently issued a five-year STEM Education Strategic Plan, recommending five high-priority investment areas: (1) Improving STEM instruction, (2) Increasing and sustaining youth and public engagement in STEM, (3) Enhancing the STEM experience of undergraduate students, (4) Better serving groups historically underrepresented in STEM fields, and (5) Designing graduate education for tomorrow's STEM workforce (National Science and Technology Council, 2013). Application of the MLTF for the production and distribution of Sci-Toons can potentially improve STEM instruction, by providing comprehensible and easily accessible materials for educators to use in the pedagogy; increase and sustain youth and public engagement in STEM, through viewing Sci-Toons, and enhance the STEM experience of undergraduates, as indicated by favorable attitude changes toward science reported by college students involved with the production of Sci-Toons. These materials, although not explicitly targeted at underrepresented minorities, were designed to be accessible for all learners.

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Appendix-Survey of SCG Students

Demographics

What is your gender?

Male [ ] Female [ ]

What year student are you?

Freshman [ ] Sophomore [ ] Junior [ ] Senior [ ] Other [ ] (Please Specify) ___________

What was your major when you started working with Sci-Toons?

____

When did you start working with Sci-Toons?

__________ __________

Month Year

Did you change your major?

Yes [ ] IF YES, What major did you switch to and why?

____

____

____

No [ ]

Since you began working with Sci-Toons, how many science, technology, engineering, or math (STEM) classes have you taken? If none, enter "0".

______________ STEM classes

How many of these classes were electives rather than required classes? If none, enter "0".

______________ STEM classes

IMPACTS ON ATTITUDES TOWARD STEM AND STEM CAREERS

We are interested in learning how participation in Sci-Toons has affected you.

As a result of your Sci-Toons experience, how has your ability to understand contemporary science issues (such as climate change, genetically modified foods, and the impacts of fracking) changed?

It has improved greatly [ ]
It has improved moderately [ ]
It has improved slightly [ ]
It has not changed [ ]

As a result of your Sci-Toons experience, how has your ability to explain scientific principles and issues to others changed?

It has improved greatly [ ]
It has improved moderately [ ]
It has improved slightly [ ]
It has not changed [ ]

Before Sci-Toons, how important did you feel it was for the general public to be able to understand science?

Extremely important	[ ]
Very important	[ ]
Moderately important	[ ]
Slightly important	[ ]
Not important	[ ]

After Sci-Toons, how important did you feel it is for the general public to be able to understand science?

Extremely important	[ ]
Very important	[ ]
Moderately important	[ ]
Slightly important	[ ]
Not important	[ ]

Before Sci-Toons, how difficult did you feel it was for the general public to understand science?

Extremely difficult	[ ]
Very difficult	[ ]
Moderately difficult	[ ]
Moderately easy	[ ]
Very easy	[ ]
Extremely easy	[ ]

After Sci-Toons, how difficult did you feel it is for the general public to understand science?

Extremely difficult	[ ]
Very difficult	[ ]
Moderately difficult	[ ]
Moderately easy	[ ]
Very easy	[ ]
Extremely easy	[ ]

As a result of your Sci-Toons experiences, how has the likelihood of your pursuing a STEM-related career changed?

It has increased greatly	[ ]
It has increased moderately	[ ]
It has increased slightly	[ ]
It has not changed	[ ]
It has decreased slightly	[ ]
It has decreased moderately	[ ]
It has decreased greatly	[ ]

Formative Evaluation Questions

About how much time did you spend on the Sci-Toons project?

____

How did this compare with the amount of time you expected to spend on Sci-Toons?

It was much more time than I expected [ ]
It was more time than I expected [ ]
It was about as much time as I expected [ ]
It was less time than I expected [ ]
It was much less time than I expected [ ]

How did the amount of effort you put into Sci-Toons compare with the effort of the other members of your team?

It was much greater than the other team members [ ]
It was greater than the other team members [ ]
It was about the same as other team members [ ]
It was less time than other team members [ ]
It was much less than other team members [ ]

How much of an impact did you have on the final version(s) of the Sci-Toon compared to other members of the team?

It was much greater than the other team members [ ]
It was greater than the other team members [ ]
It was about the same as other team members [ ]
It was less time than other team members [ ]
It was much less than other team members [ ]

Did you feel that you understood the scientific principles underlying the Sci-Toon(s) you worked on?

Definitely yes [ ]
Mostly yes [ ]
Most no [ ]
Definitely no [ ]

Did you feel that you understood the process of making a Sci-Toon video?

Definitely yes [ ]
Mostly yes [ ]
Most no [ ]
Definitely no [ ]

In what ways, if any, has your Sci-Toons experience influenced your education or career plans?

What did you like best about your Sci-Toons experience?

What did you dislike about your Sci-Toons experience?