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REVIEW

Using a comic book to engage students in a cryptology and cybersecurity curriculum

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ABSTRACT

This article describes the use of a comic book to anchor a cryptology and cybersecurity curriculum for upper elementary students. Perceptions about the comic book from 138 students across 11 afterschool programs were examined using survey, classroom observation, and interviews. Data analysis revealed that the comic book created a "macrocontext" to situate learners in an exciting adventure about cryptology and cybersecurity. Students found the characters relatable, and their perceptions were tightly tied to other components of the curriculum. Reading the word bubbles was challenging at first, but got easier over time. This study illustrates how comic books can anchor unfamiliar STEM content for younger learners.

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With the advent of the internet and cloud computing, governments, individuals, schools and other organizations have started transitioning much of their work online. Because so much private and sensitive information is stored digitally, cybersecurity is a major concern for national and personal security and cybersecurity professionals are in high demand (ISC² Cybersecurity Workforce Study, 2020; Shumba et al., 2013). Cybersecurity professionals protect content stored on the internet and digital devices, track cybercriminals and devise tools to prevent future cyberattacks. However, the US is experiencing a lack of cybersecurity professionals (National Academies of Sciences, Engineering, and Medicine, 2018), with 359,236 jobs needed in the US in 2020, and this number is only expected to increase (ISC² Cybersecurity Workforce Study, 2020).

The lack of cybersecurity professionals in the US is directly attributed to the unbalanced professional demographics, namely the underrepresentation of women and minority groups in the field (Shumba et al., 2013). Only 11% of information and security analysts are women, and 12% are African American (U.S. Bureau of Labor Statistics, 2021). This underrepresentation may be a pipeline issue as women and minority groups graduate with fewer STEM degrees than other groups (Shumba et al., 2013).

Educational efforts targeted toward girls and minority groups may help cultivate their interest and encourage them to enroll in STEM programs in college and join the STEM workforce, including careers in cybersecurity, and the US government has increased their investment in K-12 cybersecurity education (Chen et al., 2021). Yet, many of the cryptology and cybersecurity educational efforts are targeted toward older learners starting at the secondary level and above (e.g., Beissinger et al., 2012; Chen & Mosley, 2019; Javidi & Sheybani, 2018; Nygard et al., 2018). Additionally, while some states have recently developed or adopted cybersecurity standards, there are currently no national K-12 standards for cryptology and cybersecurity. Further, professional development and educator training on cybersecurity is only likely to exist for secondary educators

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and above, if it exists at all (Javidi & Sheybani, 2018; Pusey & Sadera, 2011). The result is that few age-appropriate, opportunities are available for younger, elementary, learners, and this is particularly true for marginalized populations (Chen et al., 2021). This is problematic because elementary students are vulnerable to cyberattacks (Mee, 2020), and elementary school is the time when individuals begin developing disciplinary preferences so curricula have the potential to be extremely impactful (Tran, 2018).

To address these needs, we developed an afterschool curriculum designed for late elementary grades (3–5), particularly young girls and children from ethnic minority groups, to introduce and cultivate interest in cybersecurity education and careers. Considering the lack of educational material on this topic for this young age group, we carefully selected and sequenced developmentally appropriate content, and designed the curriculum so it was approachable and engaging to both educators and students.

We developed the curriculum to focus on cybersecurity as well as cryptology. As the backbone of cybersecurity, cryptology is the study of secret communication and has been around for thousands of years. The principles and methods used in cryptology to encrypt and decrypt information are similar to methods and tools used in cybersecurity. Cryptology can be introduced to young children using simple pictorial codes such as emojis and can transition to more complex verbal and mathematical codes and ciphers. Thus, cryptology was deemed by our team as a natural place for us to start a cybersecurity curriculum for young learners (Paar & Penzl, 2010). The content of the curriculum includes codes, ciphers, and cybersecurity concepts from ancient to modern times and different cultures.

With the aim to cultivate student interest and awareness in cryptology and cybersecurity, we were very intentional to create a curriculum that was engaging, relevant, supportive of all learners, and easy to teach for an educator with no or little knowledge of cryptology or cybersecurity. We chose to present the curriculum as three interrelated components: an app, unplugged activities, and a comic book. These three components worked together to concurrently engage students and educators, while also present content in ways that was guided and manageable. The app featured a variety of digital activities using puzzles, games, and simulations. Learners practiced encrypting and decrypting messages using symbols, signs, and codes, and explored how computer networks work and how to protect oneself from a computer hack. Unplugged activities allowed learners to practice and reinforce these skills, just without a digital device. Despite the importance of cryptology and cybersecurity, in a needs assessment we discovered that elementary students had little knowledge of cryptology and cybersecurity and they could not describe how cryptology and cybersecurity related to their everyday life. In addition, the content of this curriculum includes a variety of concepts and historical events which take place during different time periods and are from different cultures. Therefore, we thought it was very important to provide context and connect all the activities to help learners understand the practical value of cryptology and cybersecurity. To achieve this goal, we decided to anchor the entire curriculum using a digital comic book. The digital comic book was integrated into the app, and as students moved though the app, the app would display different sections of the comic book. The comic book gave context to the digital and unplugged activities and situated the learners in an overarching story (Cognition and Technology Group at Vanderbilt, 1990). Further, comic books are a developmentally appropriate way to engage young learners learning complex content though a culturally relevant story and near-peer characters (Boerman-Cornell, 2013; Gavigan, 2014; Norton, 2003; Schwarz, 2002).

The current study was a part of a larger design-based research project (Brown, 1992; McKenney & Reeves, 2018) on designing, developing, testing, and refining the curriculum model. In current study, we describe the design of a comic book to engage elementary students in the cryptology and cybersecurity curriculum. We also evaluate the comic book design by examining students' perception of the comic book to understand how the comic book supported student learning in this curriculum.

Literature review

Comic books are multimodal texts that use pictures and words to tell a story. Comic books are popular among elementary students as they think that comic books are fun and are visually interesting and engaging (Gavigan, 2014; Norton, 2003). Because comic books tell stories through images as well as text, the images can engage learners and help them create meaning to understand what is going on in the story. Learners feel more in control of their reading and learning process because they are constructing meaning while they are reading. Also, because of the text and picture structure of comic books, learners need to make inferences about the story and predict what will happen later. In this way, comic books can engage and motivate struggling or reluctant readers, especially second and additional language learners, and build important critical thinking and literacy skills (Cary, 2006; Liu, 2004; Norton, 2003; Ranker, 2007; Rapp, 2011).

Because comic books can motivate young, reluctant, or struggling readers to engage in critical thinking and literacy, they are a popular teaching tool. Comic books have been used across curricula to introduce and explore various subject matter. An introduction to a complicated, or foreign subject can be made more familiar and approachable by using a comic book (Boerman-Cornell, 2013; Schwarz, 2002).

Specifically in STEM fields, comic books have been utilized to engage students in unfamiliar STEM content, develop student interest in STEM in informal settings, utilize role models to promote retention of women from historically marginalized populations in STEM fields, and teach elementary STEM content (Chung et al., 2016; Crane et al., 2022; Ganesh, 2013; Maryani & Amalia, 2018). In a study by Ganesh (2013), an undergraduate course in Computer Engineering used comic books to introduce abstract, theoretical concepts to students. Students traditionally struggled learning these theoretical concepts, but students who learned with the comic book had more fun learning these concepts and had better learning outcomes (Ganesh, 2013). Comics have also been used in museums to complement science exhibitions. In a study by Chung et al. (2016), museum visitors reported that they were more interested in the science and anatomy exhibitions paired with comic strips, and the comic strips helped them understand the exhibition (Chung et al., 2016). Role models in comic books have been used to promote retention of Hispanic/Latina women in STEM. A study done by Crane et al. (2022), found that undergraduate women identified implicitly with STEM more strongly when the heroin of a STEM comic book matched their ethnicity. And although not significant, Hispanic/Latina undergraduates who read a STEM comic book with a Hispanic/Latina heroin, identified stronger as a woman in STEM than the students who read the same comic book with a white heroin. There is also evidence that comic books can help elementary students learn scientific content. In a study done by Maryani and Amalia (2018), the researchers developed a comic book to teach 5th graders about plant biology. The participants reported that they enjoyed learning with the comic book because it was visually appealing, funny, engaging, and easy to understand. Researchers also found significant differences between a pretest and post-test on plant biology, so they concluded that the comic book helped improve participant's learning outcomes (Maryani & Amalia, 2018).

Comic books have also been used to anchor instruction and develop a "macrocontext" (Cognition and Technology Group at Vanderbilt, 1990) in STEM learning, which has aided in improved student learning and engagement. A study by Günbaş (2020) used animated cartoon stories as an anchor to give fourth grade students a meaningful "macrocontext" for solving math word problems. Animated cartoon stories are similar to comic books because they both use visual and text elements to tell a story. In the study, one group of participants used the animated cartoons to solve math word problems, another group used text-only stories to solve math word problems, and a final control group solved the same math word problems without a story. The group that used the animated cartoons performed significantly better on a pre and posttest about math word problems. Further, this group was the only group that significantly improved their mathematics problem solving. The author attributes this change to the meaningful "macrocontext" built by the animated cartoon story (Günbaş, 2020). Another study by Tassell et al.

(2019) used a math comic book to give a story-based, contextual anchor for students in 4th–6th grades to improve attitudes toward and engagement in math. A pretest measuring attitudes toward math found that younger students enjoyed math more than older students. In the post-test, students in classrooms that used the comic book did not have the same grade level difference, which the authors attribute to the comic book increasing math engagement and enjoyment. Further, students and educators in classrooms that used the comic book reported they enjoyed using the comic book (Tassell et al., 2019).

Theoretical framework

We drew on three theories to inform our design and evaluation of a developmentally appropriate, engaging, and culturally relevant comic book intended to cultivate young children's interest in cybersecurity and cryptology: engagement theory, anchored instruction, and culturally relevant pedagogy.

Engagement is a key prerequisite for effective classroom learning as it is critical for fostering student interest in learning and academic achievement. Engagement can increase motivation to learn STEM content and even contribute to students' career aspirations, including STEM careers (Maltese & Tai, 2011). Engaging students in our cybersecurity comic book was particularly important for our project because cryptology and cybersecurity content may be unfamiliar for educators, students and their parents, and may be perceived as technical and complicated (Javidi & Sheybani, 2018). To facilitate classroom engagement, it is important to consider at least three different facets of this construct: behavioral, emotional and cognitive engagement (Fredricks et al., 2004). Behavioral engagement includes persistence, effort, concentration, and contributing to class activities. Emotional engagement describes student affections such as interest, curiosity, and, on the other hand, anxiety, frustration, and boredom. Finally, cognitive engagement reflects the cognitive and metacognitive aspects of reflecting on one's learning, self-regulation, and flexible problem solving. All three types of engagement are overlapping and can be measured and can change over time (Fredricks et al., 2004).

Behavioral, emotional, and cognitive engagement can be facilitated more effectively using anchored instruction. Anchored instruction is a technology-centered learning approach under the social constructionist paradigm (Cognition and Technology Group at Vanderbilt, 1990). It posits that situating educators and learners within a story driven "macrocontext" helps learners actively construct knowledge. Situating learning within a story increases engagement and sustained interest in the learning problem and this approach is particularly useful for young children to increase the relevance of learning and provide an engaging context for the problem the children are solving. Anchored instruction offers several design guidelines to increase student engagement and encourage persistence though challenging content. These guidelines include using a narrative with which to introduce a complex problem and providing all the data and strategies required to answer the problem within the narrative. Additionally, anchored instruction suggests using visual rather than textual formats to present contexts to learners because visual formats can provide a more veridical representation of events compared to text. Thus, learners can form rich mental representations of the problem-based context more easily, and this is especially important for novice learners. With visual representations, learners can also develop enhanced pattern recognition skills that are important in many cryptology and cybersecurity tasks (Cognition and Technology Group at Vanderbilt, 1990).

Anchoring instruction in a personally meaningful context would be impossible without considering the socio-cultural dimensions of the curriculum and the problems and activities that children complete to advance their understanding of cybersecurity. Specifically, we were interested in exploring strategies to address the underrepresentation of African American females in the cybersecurity profession, so we drew on the framework of culturally relevant pedagogy (Ford, 2010; Gay, 2013; Ladson-Billings, 1995a) to help us best design for this population. Culturally relevant pedagogy proposes that students must be academically successful, develop and maintain their cultural integrity, and become socially critical. A way to do this is to actively incorporate

and use a student's culture in the academic content and social context of the classroom. Incorporating student culture in academic content can provide a bridge for students to connect with content they may ordinarily feel is outside of their comfort zone (Ladson-Billings, 1995a, 1995b).

Narrative is known to be an effective context for communicating understandings of STEM phenomena in meaningful and relevant ways (Avraamidou & Osborne, 2009; Levy & McNeill, 2015). Existing research on the role of narrative-centered learning with girls and African-American youth indicates that this "narratives of identity" approach can be useful for engaging female and African-American students in reading, scientific experimentation, and other learning activities (Cokley, 2005; Ellison, 2014; Taylor, 2013).

Design of the comic book

The choice to use a comic book to introduce elementary learners to the key concepts and practices behind cryptology and cybersecurity was driven by our theoretical framework which included the three theories: engagement theory, anchored instruction, and culturally relevant pedagogy.

Our design team consisted of educational researchers, developers, afterschool educators, and a visual artist. We worked in iterative phases to design and develop all aspects of the comic book. To improve the socio-cultural relevance of the curriculum, we designed the comic book as an anime fan art-styled story with young, diverse, near-peer children as characters. The major characters each have his/her own personality traits, which are introduced at the beginning of the comic book and revealed throughout the story. We designed these personal traits to be general, such as wise, brave, curious, funny, free, leader, natural problem solver, keen observer, etc. Each character plays a unique role in the problem-solving process and their dialog, jokes and reactions are written to be relatable to our target population and reflect the personality of the characters. The characters are also named to reflect their culture and personality (Akila, Bai, Carly, and Jabari, Table 1). Throughout the curriculum, the educator is prompted to discuss the characters and help learners connect to them, which is an effort to emotionally engage learners. In addition to the main characters, the comic book also included supporting characters such as Akila's grandmother, Alan Turing (the "father" of cryptology and computer science) and Ancient Greek soldiers who used secret communications in wars.

The narrative aspect of comic books was especially appealing to our design team, and we used the story to develop a "macrocontext" for learners by anchoring the entire curriculum in

Table 1. Comic Book Main Characters, Pictures, and Short Description

Character				
Name	Akila	Bai	Carly	Jabari
Description	Akila's name means "wise." She is a natural leader, and the comic book story is told from her perspective.	Bai's name means "person of clairity." She is one of the three main friends in the story. She is a kean observer and a natural problem solver.	Carly's name means "free woman." She is the third friend in the group. She is brave, curious, and funny.	Jabari's name means "brave one." Jabari is Akila's little brother. He finds the tablet after the girls get sucked into the cyberworld and helps the girls solve puzzles from outside the tablet.

Figure 1. Example of a comic book frame.

the comic book story. The story is told through the perspective of a young African American girl, Akila and begins with three friends accidently finding Akila's grandma's mysterious West African curio in Akila's garage. When Akila tries to use her tablet to take a picture of the curio, the tablet inexplicably sucks the three friends in to the cyberworld (Figure 1). With Akila's little brother, Jabari's, help through the tablet, Akila and the other characters crack codes, solve puzzles and learn the history of code breaking and making as they try to escape the cyberworld. Their adventure takes the characters through space and time to meet relevant people who have worked in cryptology and cybersecurity.

The comic book modality gave a fictious back drop to allow the characters to travel to places with vast cultural, temporal, and historically differences like ancient Greece, the Chihuahuan desert, and the cyberworld. It also allowed the characters to meet important historical figures like Alan Turing, and Akila's grandmother who worked as a codebreaker during WWII in the Women Accepted for Volunteer Emergency Service (WAVES) program. The places and people highlighted in the story were chosen to further promote socio-cultural relevance by integrating relevant social studies, history and language arts connections. These included highlighting the "invisible" African American cryptologists and focusing on known vulnerabilities in technologies relevant to children's everyday lives such as texting, social media, and online games.

The story in the comic book was written to guide learners though a sequence of concepts and skills introduced in the curriculum. The characters gave context to the cryptology and cybersecurity puzzles and problems, and learners solved the problems for the characters by cracking codes or breaking ciphers in either digital or unplugged activities. The design and flow of the comic book weaved the unplugged and digital activities together so that the learners were doing the same things the comic book characters were. The story guided the learning events, thereby creating a "macrocontext" to anchor all of the learning activities in the curriculum and tie them together into one cohesive story. For example, one of the cybersecurity concepts introduced in the curriculum is social engineering. Social engineering is the act of manipulating people into performing certain actions or disclosing confidential information that can be used to access a computer system. We used the comic book to introduce social engineering though a story where our heroes must crack a lockbox with a several digit combination lock. Alan Turning found a note which included personal information of the owner of the lockbox (Figure 2). Learners must use the information in the note to crack the combination lock in the following digital activity. After they crack the code, the comic book is used to explain the cybersecurity practice social engineering, which the learners just used (Figure 3).

We often used the comic book as a cliffhanger to keep students engaged between activities. For example, during one scene, Akila's little brother, Jabari's, tablet is being attacked by bots. The comic book stops at a cliffhanger where the girls are running away from the bots asking for Jabari's help (Figure 4). In the next frame of the app, learners participate in a digital activity

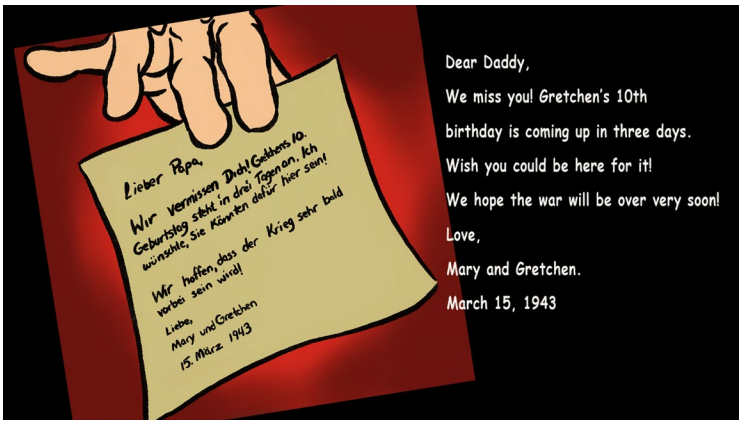

Figure 2. Comic book frame that gives learners the information they need for the next digital activity.

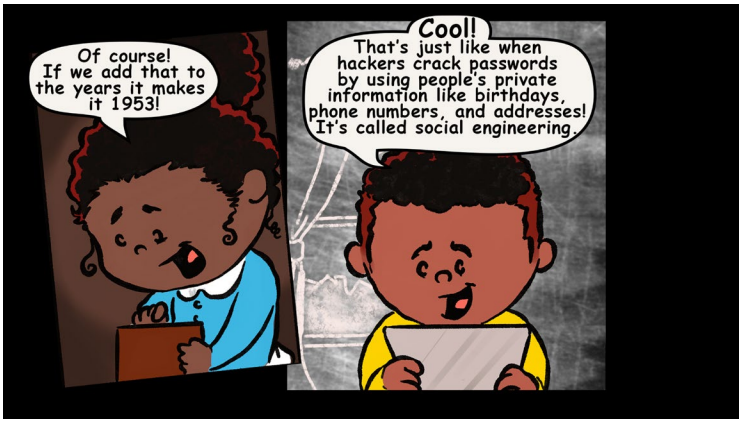

Figure 3. Comic book frame that explains the concept of social engineering.

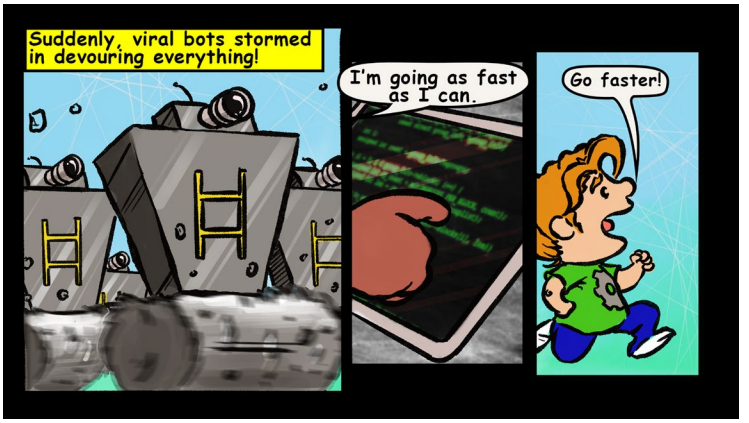

Figure 4. Comic book frame that stops at a cliffhanger where viral bots are attacking the characters.

to "fight" the bots for Jabari by selecting a bot and answering a question about cybersecurity (Figure 5). After the digital activity, the comic book continues - Jabari successfully thwarts the hacker, and the girls receive a pop-up message with a link that asks for their information to claim a prize. The comic book stops again and learners discuss if it is safe to click and link and related cybersecurity issues such as phishing. Learners then participate in an unplugged

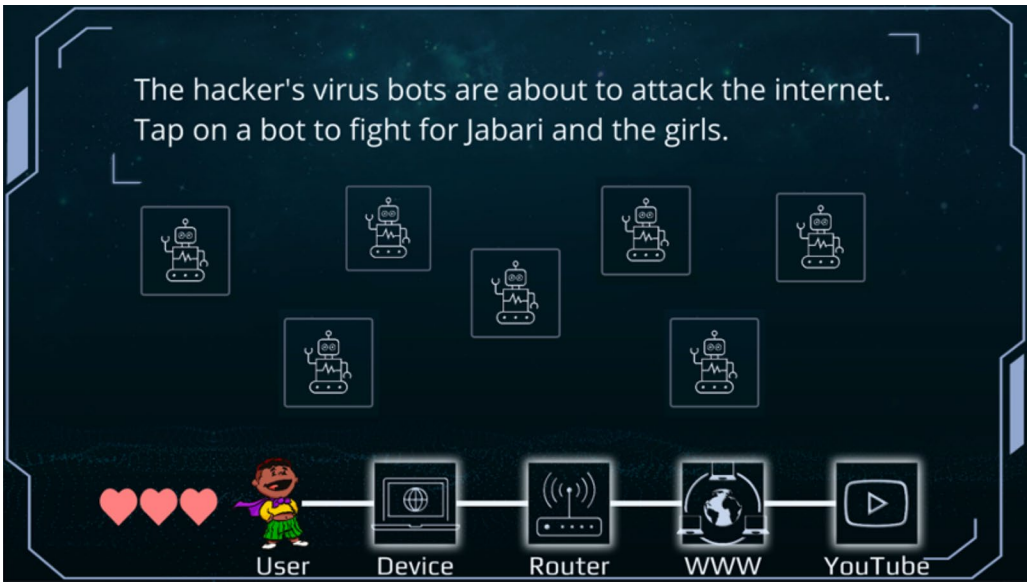

Figure 5. App activity after the cliffhanger that bridges the comic book story to the app game.

activity "Phishing for information," in which learners distinguish private and personal information and decide if it is safe and unsafe to share the information online. The cliffhangers maintained continuity of the story, and were designed to hold the emotional and behavioral engagement of the learners as they completed the app activity to help the comic book characters.

The visual medium of the comic book was something our design team was particularly excited about. Anchored instruction suggests presenting learning problems using a visual medium (Cognition and Technology Group at Vanderbilt, 1990). Further, visual media can better present the visual, spatial, and numerical patterns associated with code breaking and help learners develop pattern recognition skills which are required in cryptology and cybersecurity, as well as other STEM fields. Finally, the visual medium allowed us to minimize the use of text, which could further engage our target population. The dialogue in the comic book was written as word bubbles and we carefully considered the number of frames each page should include to ensure the images and word bubbles did not overwhelm elementary learners. The realization of the visual medium was performed by a professional artist, who also wrote the scripts for the story.

Based on feedback from pilot implementation, we added audio narration to the word bubbles and enlarged the font size in the comic book. We carefully selected voice actors to represent the gender, age, cultural background, and personality of the comic book characters to increase the socio-cultural relevance of the narration. For example, a British male adult was invited to record the text for Alan Turing. Educators or students could choose to enable audio narration by toggling on the audio narration option at the beginning of each chapter. Each word bubble in the comic book was linked to the audio narration for that particular utterance. To play the audio, learners simply needed to tap the word bubble. This design provided cognitive support to learners who needed the audio for just a few words and for learners who needed audio for the entire comic book. Also, learners who chose to listen to all of the dialog had to constantly interact with the comic book, which helped increase cognitive and behavioral engagement.

Method

Research question

The above examples highlight the design decisions utilized for creating and using a digital comic book used to anchor our cryptology and cybersecurity curriculum, and how the design was

influenced by engagement theory, anchored instruction, and culturally relevant pedagogy. The current study employed a general qualitative inquiry approach (Kahlke, 2014; Lincoln, 2010) which used qualitative data and some descriptive quantitative data to examine students' perceptions of the digital comic book that anchored this curriculum. We were particularly interested in student perceptions because the content of our curriculum is technical, and not often introduced at this age level. Through examining student perceptions, we aimed to understand more about the comic books use, and its role in student's perceived learning of complex STEM content in an afterschool setting. This study employed qualitative and quantitative means to address the following research question:

- What are elementary students' perceptions of the comic book and its use in a cryptology and cybersecurity curriculum for afterschool programs?

Participants

Students and educators from thirteen afterschool programs across three states in Southeastern US implemented the curriculum and the comic book in Fall 2021. The afterschool programs were recruited using several considerations including target population, ease of driving distance for data collection, 1:1 technology availability and willingness of the instructor to participate in professional development. Three of these programs served only African American children and families, two served only girls, one worked with students with learning differences, one worked with students from refugee families, two were located in city public schools, and two were located in rural public schools. Our sample is representative because the target population of this curriculum is underrepresented students in STEM. All of the students and educators who participated in the curriculum consented to participate in the study before starting the program.

Qualitative data including interviews and observation notes were collected from two programs local to the research team because the researchers could physically observe and interview participants in those locations. Seven children participated in 20-minute semi-structured interviews on a voluntary basis. A survey of student perceptions was collected from 138 elementary aged children from 11 afterschool programs who completed the curriculum and participated in the post-implementation comic book survey.

Data sources

We collected data about student perceptions of the comic book using interviews, field notes taken during observations, and an age-appropriate survey. All three sources triangulate to improve the credibility and validity of the findings.

Interviews

We used semi-structured interviews (Patton, 1990) to explore students' perceptions of the comic book, the characters and the story. Following the interview protocol refinement framework (Castillo-Montoya, 2016), we ensured our questions aligned to our research goals, related to engagement, and sought to help facilitate a conversational tone throughout the interview process. We also solicited feedback on the protocol from colleagues with experience interviewing children and informally tested questions similar to those on the protocol during our interactions with children as they participated in the curriculum.

We implemented research-based best practices for interviewing children such as trying to make them comfortable and ensuring them that there were no right or wrong answers, conducting the interviews soon after they had interacted with the comic book, adapting the way we asked questions based on how students responded, member checking throughout the interview, and providing them with access to the comic book during the interview so that it might serve

as a retrieval cue (Clark, 2005; Danby et al., 2011). Interview questions were also written in simple terms with probes to use as needed. For example, we asked the children "What did you think about the comic book story?" and one of our probes was "what did you think about the plot in the comic book" because we know both story and plot are vocabulary words addressed in our participants' Language Arts classes.

Observation field notes

Several researchers from our design team observed each implementation session in person. This prolonged engagement lasted either 8 or 10 weeks, depending on the program, as researchers developed a rapport with students and educators. During observations, researchers collected descriptive field notes, which were another important data source for this study (Bogdan & Biklen, 1998). These field notes were collected as part of an observation protocol developed and refined by the researchers throughout project. The observation protocol was designed to capture behavioral, cognitive, and emotional engagement, which aligns with our theoretical framework. Before use, each researcher was trained on how to use the protocol, and after the first use, and as needed, researchers resolved any discrepancies or questions on how to use the tool. After the final observations when each program finished implementation, the field notes pertaining to the comic book were pulled out from the observation protocol and organized in an Excel spreadsheet. Field notes included descriptions of communications and actions that gave us insight into how students were perceiving the comic book. For example, researchers documented what students said about the storyline and characters and how they acted while reading the comic book.

Survey

Survey responses provided descriptive quantitative data on children's perceptions of the comic book and its use in the curriculum. We used a five-step questionnaire development process recommended by the Institute for Education Sciences to collect data on students' perceptions (Harlacher, 2016). This survey was designed to help us understand how the comic book was working in our particular context, and was not meant to be generalizable. This process involved making sure the survey items aligned with the research goals, writing questions that could be answered by young children, ensuring brevity, and formatting the survey for easy use. The survey included eight items (Table 2) related to students' perceptions of the comic book in general, their perceived connection to the characters and their adventures, and their perceptions of the illustrations and other features of the comic book. The development and selection of these items were influenced by engagement theory, one aspect of our theoretical framework. Students responded to each item using a 5-point Likert scale ranging from Strongly Disagree to Strongly Agree.

Procedures

This study was conducted in Fall 2021. The implementation of the curriculum lasted 6 to 10 weeks, based on the programs' own schedule. The two local programs implemented the entire

Table 2. Survey Items and Descriptive Statistics for Survey Data

Survey items	Mean	SD
I enjoyed reading the comic book.	4.33	0.98
I liked the overall look of the comic book (what the comic book looks like).	4.20	1.10
I can relate to one or more of the comic book characters.	4.13	1.09
I liked the comic book characters.	4.12	1.22
I think I helped the kids in the comic book by using codes, ciphers, and cybersecurity knowledge.	4.03	1.12
I think the comic book was the correct length (not too long or too short)	3.97	1.19
I liked the comic book story	3.96	1.13
The comic book story helped me understand the activities we did	3.60	1.34

Note. 1 = Strongly disagree, 5 = Strongly agree.

curriculum for 8 and 10 weeks. Two researchers observed all the implementation sessions and took abundant field notes. Before the last two classes during recess time, seven students were interviewed by the two researchers. The survey was administered after the educators finished the curriculum implementation. The time of survey administration varied because the 11 programs finished the curriculum at different times.

Data analysis

Survey data related to students' perceptions of the comic book were analyzed using descriptive statistics and compiled in table format. We followed Saldaña's recommended method for coding qualitative data (Saldaña, 2016). First, researchers independently open-coded interview transcripts and observation fieldnotes keeping in mind our goal to understand elementary students' perceptions of the comic book and its use. Through this open-coding process we individually sought to identify the content and essence of our data. One researcher then served as the "codebook editor" (Saldaña, 2016, p. 36) as we met to compare, contrast and synthesize our individual codes. Once we felt our codes aligned to our research question and represented the differing insights and perspectives each researcher brought to the coding process, we sought to understand the "consolidated meaning" of our codes through categorization (Saldaña, 2016, p. 36). Finally, we considered how to represent our categories as higher-level, general themes using snippets and segments of quantitative and qualitative data to illuminate their meaning.

Results

Our study participants generally had positive impressions of the comic book (Table 2). In particular, they had positive perceptions of the story, the characters and their involvement in the comic book. Qualitative data support that students had positive impressions of the comic book with researchers observing students saying "NOOOO!!" and "I really want to continue it" when the comic book ended. Other students used words like "really cool," "nice," and "creative" to describe what they thought about the comic book. One student even likened the comic book to a movie.

> It's a pretty good story. It feels like a movie. You're watching a movie like you… mostly I think was a pretty good plot because it talked about this girl who was with her friends decoding things. And then they went on, they went inside the tablet and then they had to figure out how to get out, and this and that, and it felt pretty good.

Students perceived the comic book as an exciting adventure. Researcher field notes describe students as eager to read the comic book, and students read the text with emotion. When reading the comic book, students would interject thoughts like "Oh there's that symbol again" and "I love that face!" which displayed an affective connection to the comic book and the story. Nora explained "I like the story because I really like nonfiction, fictional stories and stories that have adventure." Byron described the story as an "adventure like where you always try to solve stuff."

Qualitative data helped further illuminate students' perceptions of the comic book. In particular, the following themes emerged during our data analysis:

1. Students' perceptions of the comic book were tightly tied to their perceptions of the rest of the curriculum (i.e., digital and unplugged activities).
2. Students perceived that they contributed to the unfolding of the story in the comic book, which helped them learn new concepts and skills.
3. Students perceived reading the word bubbles as challenging at first, but easier over time with support from educators, peers, and audio narration.
4. Students perceived the characters as relatable to themselves, their peers, and their educator.

Students' perceptions of the comic book were tightly tied to their perceptions of the rest of the curriculum

When asked about the comic book, students talked about their perceptions of the comic book story in conjunction with other digital and unplugged activities, and how the comic book helped them understand these activities. Students were able to talk about the comic book story, however they also talked about other parts of the curriculum as if they were a part of the comic book. For instance, when asked to give an example of the comic book helping them understand different types of ciphers and codes, a student told us that the comic book could get her excited and surprised when a problem or a new idea was introduced. She then explained that the educator would discuss with the class to reflect on the story and brainstorm possible ways to solve the problem; afterwards, students would try to solve it by doing the digital and unplugged activities. When we asked about what students learned in the comic book, Byron said "The pigpen cipher…. You had to use the like normal letters and the dots on it to get that code and then it will translate it into basically what the code is or the message." Byron discussed the tablet app game where students dragged and dropped pigpen symbols to solve secret messages. The comic book only introduced the students to the name and symbols of the pigpen cipher and is not interactive.

We also found that students confused other app features as the comic book features. For example, when students talked about how they felt about the comic book, multiple students mentioned that they liked the lock screens. We integrated lock screens in the app after comic book sections and digital activities to help the educator keep learners at the same place and transition between the different curriculum components, thereby supporting behavioral and emotional engagement. Each lock screen could be opened using a unique secret touch gesture which made lock screens feel a little like a secret puzzle. Students described how "fun" and "cool" the lock screens were, indicating that students perceived them as part of the comic book. However, lock screens were used throughout the curriculum.

Students perceived that they contributed to the unfolding of the story in the comic book, which helped them learn new concepts and skills

The survey item "I think I helped the kids in the comic book by using codes, ciphers, and cybersecurity knowledge" had the mean score of 4.03, which indicated that a majority of the students felt that they contributed to helping the comic book characters solve problems and escape the cyberworld. In classroom observations, we heard students express their thoughts as if they were the comic book characters or their friends. For example, when the comic book characters received a phishing email, a girl mumbled "I'd delete that [email]." When the students found a map was hidden in a comic book frame, another student anxiously said "it's under your pillow, girl!" In the interviews, many students perceived that they were part of the comic book and provided us detailed examples to explain what they did to help the comic book kids to solve their problems. A girl reported that "we are all going on an adventure all together with the comic book girls. We are all our own characters, their own characters, and we are all going on an adventure together." Kayla shared "helping them [the characters] go up the stairs, then it will be at the end and they will grow mostly. I felt like I was helping the characters by doing some of the activities." The "going up the stairs" Kayla mentioned was a part of Chapter 2 where the characters Akila, Bai and Carly found a staircase with morphemes on each step. The comic book paused at a cliffhanger when the characters realized they could only climb the staircase if they stepped on the steps with correct morphemes to make meaningful words (Figure 6). Right after the cliff hanger, students completed a series of digital and unplugged activities where they connected morphemes to make meaningful words. When the comic book resumed, the characters successfully climbed the staircase.

Students reported that they learned a lot of new knowledge and skills as they helped the characters solve problems. Nora said "I like how it teaches you new things… I learned different

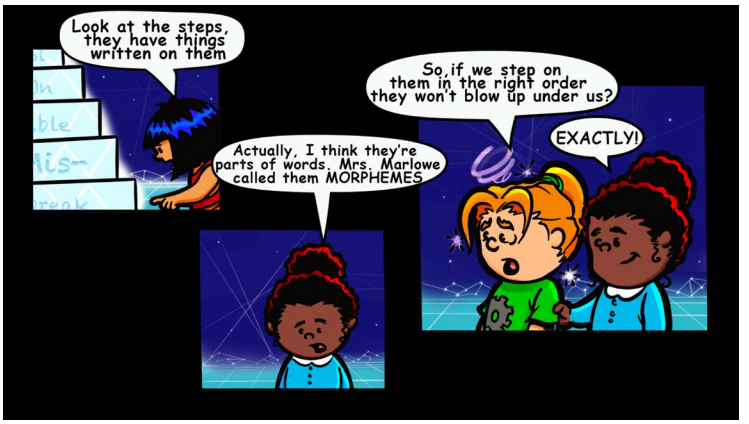

Figure 6. Comic book page that presents a problem which is solved by the students in subsequent unplugged and digital activities.

types of codes that I never ever knew before." Students also described how the comic book used problem solving and puzzles for learning. Byron said "The story is, is really cool because it gives me a puzzle always to solve and it makes me work too, so it's not like a normal story of a comic book that like normal books." Students also referenced vocabulary and concepts from the comic book during interviews, which indicated that they learned about cryptology and cybersecurity in a historical context. A student named Ana said "we're learning about different language, what they did in World War II, how women served in World War II, how WAVES began, and stuff like that, and how codes work." Ana is referencing the historical events told though the comic book, and WAVES, introduced in the comic book, was the group of women coders who served during World War II. Other students used new vocabulary and concepts introduced in the curriculum such as encipher, decipher, pigpen, Caesar wheel, and scytale, when talking about the comic book.

Students perceived reading the word bubbles as challenging at first, but easier over time with support from their educator, peers, and audio narration

Students told us that reading the word bubbles was confusing at first, but got easier over time. Nora said "sometimes I get confused" when asked how she read the word bubbles. When asked the strategies students employed to read the comic book, the children reported that listening to their peers, asking for their educator's help, and listening to the audio narration all helped them read the comic book. Nora explained "when I heard people reading the comic book, I noticed I was supposed to read to the right… I feel ok now." Devon relied on support from his educator and said "Yeah, first it was kind of hard. But then I asked one of the educators and they kind of give me the, like, a hint kind of. Then… I understand." Kayla perceived following the audio narration as easier than reading. She commented that it helped her better understand the content. Kayla likened the audio narration to audio books and said "cause when you read audiobooks, you understand was going on and it'll go way more faster instead of being there for five hours." Devon also perceived the audio narration as helpful and said "It was kind of like giving our mouths a break, and our, kind of, ears listen."

Students perceived the characters as relatable to themselves, their peers, and their educator

Students perceived the characters' personalities and skills as relatable to their own, and they cited commonalities among their personalities. Leah said she could relate to "Akila because she's like me cause sometimes she's funny, and she's smart." Similarly, Kayla said she could relate to

Bai "because she is a problem solver… when it comes to my cousins, it's mostly like problem solving all day." Ana mentioned both the character's personality and design when she said "I can relate to Carly because she is strong. And she also has a ponytail which I really like." However, the majority of students cited personality traits they could relate to instead of appearance or race.

Students also perceived the characters as relatable to their peers and educator. In one researcher's field notes, a student was observed saying the name of another student and "smart boy!" after they read Bai was a problem solver and a good observer, indicating that this student related their peer to Bai. Another student was observed pointing to their educator when Akila was introduced as a natural leader.

Discussion

Using survey, classroom observation, and interviews, we explored students' perceptions of the comic book and found that students generally enjoyed reading the comic book due to an engaging story and relatable characters.

A key finding of our study was that students' perceptions of the comic book were tightly tied to their perceptions of the rest of the curriculum. We interpreted this result as students recognizing the comic book as an integrated and indistinguishable part of the curriculum. Students perceived the comic book, app, and unplugged activities as one coherent story. This type of storytelling is known as transmedia storytelling (Jenkins, 2007), whereby a unified story is told across multiple modalities. Each modality contributes a unique feature to the story, so learners are captivated by the learning experience and enter into a state of flow, or ultimate engagement (Csikszentmihalyi et al., 2021). Engagement is the "holy grail" of any user-centered design product from books, to games, to social media (Cooper et al., 2014). Understanding the narrative via multiple media that work in concert together helped students engage at higher levels of cognitive, emotional and behavioral engagement. This was supported by other findings of this study, such as the role of audio narration in the cognitive engagement of children who had trouble following written text in the comic book bubbles.

Another key finding of this study was that students perceived that they were part of the comic book and that it helped them learn new concepts and skills. Learners were so captivated by the multimodal, transmedia story that they perceived they were part of the comic book. Children felt that their actions helped the comic book characters solve codes and ciphers, make decisions, and ultimately escape the cyberworld. This is evidence that the comic book served as a useful tool to anchor the curriculum and provided an important "macrocontext" for learning, a major part of anchored instruction (Cognition and Technology Group at Vanderbilt, 1990). This "macrocontext" situated learners within the story and gave them a media-rich, engaging context to solve the learning problems and progress through the curriculum.

As a "macrocontext" for students' problem solving, the comic book also supported students' engagement and interest in learning the content. We saw evidence of student engagement in all three domains and, data collected in the beginning, during, and at the end of the curriculum implementation revealed that this engagement was sustained throughout the entire program. Students were engaged affectively because they reported they enjoyed the comic book adventures and perceived them as exciting. Our participants also related to many of the characters on an emotional level, likening themselves to the comic book heroines and heroes. Students were engaged cognitively because they shared that they had learned many new cryptology and cybersecurity concepts and skills which was evidenced by them using core vocabulary and content during interviews. Behavioral engagement was evident during classroom observations and in researchers' field notes because students stayed on task, eagerly contributed to class activities and persisted in the face of difficulty (e.g., when students had difficulty reading word bubbles). Cultivating all three types of engagement is critical for learning, and perhaps especially important when learning content that is unfamiliar and perceived as difficult (Fredricks et al., 2004).

The evidence that students developed new skills and learned new concepts was very encouraging. In this project, we took complex topics, cryptology and cybersecurity, that are not typically addressed in elementary education and made them approachable and interesting for young learners. Students were enthusiastic about the puzzles they were solving and discussed content from the curriculum during interviews. Along with evidence of cognitive engagement, we saw this as evidence that the comic book provided a "macrocontext" for learning. Students were able to engage with new concepts, co-construct knowledge during comic book discussions and engage in non-routine problem solving in digital and unplugged activities. It's possible that the comic book allowed learners to create mental representations of the complex topics, which is critical for young learners (Cognition and Technology Group at Vanderbilt, 1990). A number of students also discussed the historical aspects of the curriculum during interviews, particularly the WAVES program during World War II, which we used in our story to highlight the "invisible" role of women and African Americans in cryptology and the war effort. This is evidence that students found this content socio-culturally relevant.

It was surprising to us that students perceived the comic book word bubbles as challenging at first. This finding deviates from some of the literature referenced in the literature review, as we expected comic books to be easier to read for younger and struggling readers (Gavigan, 2014; Norton, 2003; Ranker, 2007; Rapp, 2011). However, the students in this study perceived the word bubbles as difficult to read at first and shared that they didn't always understand their order. During our design and development process, we increased the size of the text in the word bubbles to make it more readable, yet more work should be done to support student's comic book reading practices. Although this was a struggle at first, students overcame this issue with help from peers, educators, and audio narration. Additionally, this challenge did not appear to impede students from engaging with the comic book or from the comic book developing a "macrocontext" for learners.

An encouraging finding was that students perceived the comic book characters as relatable to not only themselves, but their peers and their educator. The evidence that students were able to relate to the characters is further empirical support that the story served as a "macrocontext" for the learners and they felt situated within the story, which likely impacted our participants' overall emotional, behavioral and cognitive engagement (Cognition and Technology Group at Vanderbilt, 1990).

It was interesting that the majority of students related to characters' personality and skill traits rather than race or physical appearance. We chose to create the comic book characters as near-peer and racially diverse to support the socio-cultural relevance of the curriculum and incorporate students' cultures (appearance, ways of learning and knowing, and expressive strategies) into the content, as is suggested by culturally relevant pedagogy (Ladson-Billings, 1995a, 1995b). Therefore, we expected students to relate more to the way the characters looked. Instead, we observed that students related to the individual strengths of each character, how the characters approached solving the problems, and how friendly and supportive they were of each other. Students connected more with the traits and personalities of the characters which were evident though the story in the comic book. This is evidence that the narrative played a paramount role in the learning, which supports a "narratives of identity" approach that is known to improve the socio-cultural relevance of the story and engage children in reading and STEM learning (Cokley, 2005; Ellison, 2014; Taylor, 2013).

Based on the results of this study, the following insights may be useful to designers and educators teaching cryptology and cybersecurity, or other STEM content, to younger learners. The comic book was useful for our curricular context because it created "macrocontext" which helped young learners engage, develop interest, and learn complex content. The "macrocontext" connected each part of our transmedia curriculum and learners felt part of the comic book that weaved digital and unplugged activities together into one narrative. We also found the narrative allowed for near-peer characters which engaged and facilitated connection between students and content, and students were more drawn to the personality traits than the physical appearance of the characters. In future designs,

we will carefully scaffold comic book reading, such as suggesting educators and students read the comic book aloud at first, as several students perceived this as challenging.

Our study also has limitations. First, our survey instrument was developed for this study, and was not meant to be generalizable to the larger population. Second, we only captured student perceptions, which offer just one lens to evaluate the design of the comic book. Future research could include using more lenses such as student performance or educator perception, to evaluate the comic book design. Third, we did not examine the impact of comic book use on student learning performance or their engagement of the curriculum, which we aim to explore in the next implementation.

Conclusion

Cryptology and cybersecurity are new to many K-12 students. To introduce these complex domains to elementary students, especially girls and ethnic minority students, we designed a comic book that addressed key cybersecurity and cryptology concepts and skills relative to the socio-cultural and historical context and provided problem solving scenarios for students using a fictious cyber adventure of three girls and a boy. Cognitively, emotionally, and behaviorally engaging young learners in STEM content and conveying the cultural relevance, academic importance, and practical value of the learning experience is extremely important to young learners' career interest and STEM identify development. In our approach, we utilized a comic book to anchor the curriculum and create a "macrocontext" which introduced the content through a culturally relevant fictional but historically based story, situated learners within that story, and weaved the digital and unplugged activities into a cohesive narrative. Although our participants perceived to have difficulty with reading the comic book at first, this did not deter them from engaging with the curriculum, relating themselves and others to the characters, and situating themselves within the story to the point where they felt they were helping the characters themselves. Ultimately, learners had an overwhelming positive experience with the comic book and the curriculum and perceived they learned many new things. Our data show that the comic book was instrumental in engaging young children in cryptology and cybersecurity content. Similar to the approach employed in this project, designers and educators with similar goals and contexts could consider anchoring their curriculum in a comic book driven narrative that serves as a "macrocontext" for engagement and learning and anchors the curriculum in a powerful story that is both relevant and captivating.

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