Cultivating Computational Thinking

in Upper Elementary & Middle School Learners through Playing *Zoombinis*

December 17, 2019

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Recommended Citation Barchas-Lichtenstein, J., Brucker, J.L., Voiklis, J., Thomas, U.G., Fraser, J., Shane-Simpson, C., & Field, S. (2019). Cultivating computational thinking in elementary & middle school Learners. Knology Publication #NSF.051.213.05. New York: Knology.

Date of Publication December 17, 2019

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This material is based upon work supported by the National Science Foundation under Grant #DRL-1502882, *Zoombinis*: The Implementation Research Study of a Computational Thinking Game for Upper Elementary and Middle School Learners. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

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Knology Publication # NSF.051.213.05

Executive Summary

With funding from the National Science Foundation, EdGE at TERC (EdGE) launched an implementation research study in 2015 to understand the educational impact of a wide-scale re-release of its award-winning game: *The Logical Journey of the Zoombinis* (hereafter *Zoombinis*). The impetus for the study was increased attention to cultivating and developing Computational Thinking (CT) skills as part of K-12 curricula across the United States, as well as educators' growing interest in using games in the classroom.

With the recent re-release of *Zoombinis*, which moved the game from being exclusively played on computers to wireless devices including tablets, EdGE saw an opportunity to contribute to the body of knowledge in cognitive and learning sciences. Specifically, the investigators sought to understand how student learners build implicit knowledge of CT skills, demonstrated through use while playing *Zoombinis*, and how educators – teachers, parents, informal educators, and others – can leverage that game-based learning to improve explicit learning of CT. EdGE also sought to explore ways that *Zoombinis* could support equitable improvement in classroom learning.

EdGE selected Knology (formerly New Knowledge Organization Ltd.) as the evaluation partner for its research study. Knology was tasked with assessing *Zoombinis* implementation needs among educators and students, and the effectiveness of bridge materials developed for teachers using the game in their classrooms. Knology also examined game-based measures of teacher-assessed and implicit CT skills and classroom performance to assess whether CT learning minimizes differences between students with different educational needs.

Results from the implementation research study activities validate the value of *Zoombinis* as a tool for teaching computational thinking in classrooms. Teachers who implemented the game said that the game has helped broaden student participation in classrooms. They report that some students who once struggled with learning through other means were able to grasp the concepts that the *Zoombinis* puzzles teach. Finally, teachers also said that the game brought out leadership skills in students who were not usually class leaders.

Much has changed since the *Zoombinis* study began four years ago. Most of the challenges that teachers initially saw with bringing *Zoombinis* into the classroom – cost, insufficient access to technology and computers, for example – are no longer significant barriers for most of the schools in the study. Students also have far more access to personal computers, tablets, and other devices at school than they did when the study first launched in 2015.

Furthermore, the definition of CT has also solidified in the intervening years through the efforts of groups such as the International Society for Technology in Education. With that change has come an evolution in some of the terminology used to talk about CT skills. Shifts in technology have helped clarify the importance of cultivating CT skills in students. For the current generation, who is growing up in an age where technological developments move at a rapid clip, these skills are only going to gain in importance. Not only is teaching children to think in this way important, it is also crucial to understand the best ways to support the different kinds of learners that are present in school classrooms and other learning environments.

Perhaps one of the biggest takeaways from this study emerged from analysis of the teacher logs and focus groups. Teachers who participated in the implementation study claimed they would use *Zoombinis* as a teaching tool in their classrooms in the foreseeable future. More importantly, these data revealed that *Zoombinis* provides a wide array of access points that can effectively support different kinds of learners. Based on those initial suggestions from teachers, this evaluation includes details from some early research that explores the extent to which CT learning may equalize the performance of students with and without Individualized Education Plans.

Together, these results suggest that further examination of this game-based experience might 1) benefit students with different learning needs and 2) help create teacher tools for more intentional support of those learners, as well as 3) develop extensions to the game that specifically support diverse types of learning needs. Future studies could, for example, examine in greater depth whether game play can bridge learning gaps between different types of learners in the same class, or possibly create opportunities for collaborative learning between learners with varying strengths.

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Introduction

With funding from the National Science Foundation (award #DRL-1502882), EdGE at TERC (EdGE) launched an implementation research study in 2015 entitled *Zoombinis: The Implementation Research Study of a Computational Thinking Game for Upper Elementary and Middle School Learners*. The study aimed to explore teachers' access to and use of the award-winning educational computer game, *The Logical Journey of the Zoombinis* (hereafter *Zoombinis*), in their classrooms. The game, which first debuted more than 20 years ago, requires players to solve puzzles that deal with logic, representations, and sequential thinking.

The current project focused on understanding the impact of the 2015 re-release of the educational computer game. Compared to its predecessor, the updated version of Zoombinis made the game accessible on tablets in addition to computers, and targeted a much broader demographic — ages 8 and above. With the re-release, EdGE saw an opportunity to conduct innovative research in cognition and the learning sciences about Computational Thinking (CT) in classrooms. CT is defined as *"the conceptual foundation required to solve problems effectively and efficiently (i.e. algorithmically, with or without the assistance of computers) with solutions that are reusable in different contexts"* (Shute, Sun, & Asbell-Clarke, 2017, p. 151).

Game-based learning is a natural fit with CT. That's because games have the capacity to engage players with broader ways of thinking that align with CT frameworks, including tolerance for ambiguity, persistence in problem solving, and abstraction across applications (Wing, 2006; CSTA, 2011). *Zoombinis*, in particular, teaches four core facets of CT — problem decomposition, pattern recognition, abstraction across applications, and algorithmic design — in fun and engaging ways. Game players immerse themselves in problem-solving situations that involve experimenting with game mechanics to understand the rules.

Existing research indicates that educational games are rife with opportunities to encourage and measure implicit learning (Thomas & Brown, 2011). EdGE has built on this research by asking educators to help learners bridge game-based learning to explicit knowledge. These studies (e.g. Rowe, Asbell-Clarke, Bardar, Kasman, & MacEachern, 2014) show that when teachers connect STEM content in games to classroom activities, students who are less academically inclined better understand science-related content and concepts. Furthermore, approaches that require users to begin with trial and error, coupled with helpful feedback and a system of rewards, have been shown to promote motivation and sustained engagement in games (National Research Council, 2011).

Building on these studies, EdGE partnered with researchers from the learning sciences and assessment community to develop novel methods for assessing CT. Their efforts included looking at gameplay strategies as evidence of implicit CT learning. EdGE proposed the implementation study to identify the strategies that players in upper elementary and middle school use to solve puzzles in the game, and to help educators use these strategies to improve explicit learning of CT in this audience. An expected outcome of this research was the development of supportive learning materials and assessments for educators and researchers focused on CT.

The implementation study sought to answer three specific research questions:

1. What strategies do players develop during *Zoombinis* gameplay that may provide evidence of implicit CT?
2. How can teachers leverage implicit knowledge developed in *Zoombinis* to improve formal (explicit) learning of CT?
3. How can a large-scale commercial game be used for broad and equitable improvement of CT?

As a central part of the implementation study, EdGE provided bridging materials to help teachers use *Zoombinis* in their classrooms. The goal of these materials was to help teachers make learning explicit. Materials included charts, data tables, posters, walkthrough strategy videos, Zoombinis character cards, worksheets, role playing activities, and Google slides. Each teacher also had access to an EdGE buddy who was assigned to help them navigate the platform and answer questions. The goal of these materials and resources were to help teachers connect *Zoombinis* activities to their own standards, particularly in the area of CT. There is no prescribed curriculum but rather a series of flexible puzzles and activities designed to be used in a range of contexts.

Knology (formerly New Knowledge Organization Ltd.) was the external evaluator for the study responsible for conducting front-end, formative, and summative evaluations of the implementation efforts. Ultimately, the partners decided that Knology would focus on evaluating data from teachers while EdGE would focus on analyzing data related to student outcomes. As a result, Knology's evaluation efforts focused on research questions 2 and 3, while EdGE's efforts focused on answering research question 1. However, Knology used EdGE's algorithms developed for research question 1 to compare different groups of students to explore question 3.

Knology's front-end evaluation assessed teachers' needs with an eye towards helping EdGE develop materials and assessments for *Zoombinis* that would support educators working with upper elementary and middle school students. This front-end survey sought to capture information such as educator perspectives about *Zoombinis*, teachers' characterizations of technology access in classrooms, and barriers to use.

Knology's summative evaluation employed two methods for assessment: ***exit interviews*** with teachers who participated in the implementation study and ***assessment of student game play***.

Knology conducted exit interviews with educators participating in the implementation study. In these interviews, participants articulated their own understanding of and comfort with computational thinking concepts, evidence of students' implicit and explicit learning in *Zoombinis* puzzles, and the benefits of gameplay to different groups of students, including students with learning disabilities as well as participants in special and individualized education programs. This evaluation exercise also looked at how often teachers taught particular CT skills in the classroom (Barchas-Lichtenstein, Field, Danter, Brucker, & Ardalan, 2018).

As part of the summative evaluation, Knology also assessed student game play. Using student data from game logs collected by EdGE and teacher evaluations of students' CT ability, Knology explored different ways of clustering student gameplay. In particular, Knology was interested in evidence that CT might help close achievement gaps linked to neurodiversity.

These methods differed from the original evaluation plan in several key respects. See Project History below for further details.

The Game

The Logical Journey of the Zoombinis engages players in a storyline involving a cast of avatars that need to solve a series of puzzles to escape Zoombini Isle. As a first step, players create a group of 16 Zoombinis with varying attributes – they can select from five possible values of four attributes (hair, eyes, feet, and nose). These options allow for 625 possible permutations of Zoombinis characters. Figure 1, below, shows examples.

Figure 1. Zoombinis with varying attributes.

These four attributes are the basis for many of the puzzles' challenges. To solve puzzles, players have to sort, sequence, and match different characteristics in increasingly complex patterns. Each task has four different levels of complexity offering players a large variety of levels of engagement, opportunities for trial and error with well-scaffolded feedback, and rewards to promote motivation and sustained engagement.

For example, in the Allergic Cliffs puzzle, players must sort the Zoombinis into two groups based on some combination of attributes. On the easiest level, the puzzle uses only a single attribute. Figure 2 shows a case where the bridge in the background allows only Zoombinis with mohawks, while all Zoombinis with other hairstyles must take the foreground bridge.

Figure 2. Screen capture from Allergic Cliffs puzzle.

For each mistake that players make, they are penalized by losing one bridge peg. When all the bridge pegs are gone, the bridges fall and all remaining Zoombinis are stranded and lost. (In other puzzles, players lose a Zoombini per mistake.) In normal play, players can only proceed past certain milestones with a set number of Zoombinis. If they do not have enough, they must re-play games to have enough Zoombinis at these break points. However, the educational version of the game allows players to attempt puzzles out of sequence with a full complement of Zoombinis.

Overall, *Zoombinis* supports students in building at least four facets of CT:

- **Problem decomposition**, *"breaking a complex problem into smaller parts and using systematic processes to tackle each of those smaller problems"* (Shute et al., 2017, p. 151);
- **Pattern recognition**, the ability to *"identify patterns/rules underlying the data/information structure"* (Shute et al., 2017, p. 153);
- **Algorithm design**, *"the development of re-usable tools/procedures for solving classes of problems"* (Shute et al., 2017 p. 151); and
- **Abstraction**, *"finding patterns within problems and solutions, and thus being in a position to* generalize *solutions for sets of similar problems"* (Shute et al., 2017, p. 151).

See Rowe et al. (in review) for a clearer articulation of how each of these competencies is displayed in three *Zoombinis* puzzles.

Project History

Through the *Zoombinis* implementation research study, EdGE sought to examine **to what extent**, **for whom**, and **how** implicit and explicit learning of CT occurs with an eye towards helping educators leverage this learning in their classrooms. Over the years, the research implementation study changed in a number of ways, as did the evaluation plan. We discuss the original plan, the changes made, and the rationale for these changes in detail in this section.

Project Evolution

At inception, the project was anticipated to include a large-scale roll-out of the game across multiple entire school districts in the final phase and compare these data with out-of-school settings. For multiple reasons, the team decided instead to include individual teachers implementing the game outside of district-wide initiatives. Following initial explorations with a core group of teachers, the team made a decision to focus on game play associated with classroom learning and to de-emphasize the role of informal educators for this study.

EdGE also mulled over whether students should be allowed to migrate through the game on their own or if teachers should have more control over student progress. While story mode (normal game play) is available in the educational version of *Zoombinis*, teachers have considerable control over which puzzles and difficulty levels their students encounter. Based on focus groups with teachers and students, the EdGE team selected 4 of the original puzzles to focus on and expended considerable effort on developing classroom materials to support learning with those puzzles.

Furthermore, EdGE initially envisioned the project engaging multiple classes with different ways of using *Zoombinis* in the implementation study, including 1) classes that used the game alone, 2) classes that had access to both the game and bridging materials, and 3) classes that had the game, additional resources and materials, and EdGE support. Ultimately, however, the team realized that comparative study involving control classrooms, parents, and informal educators would not be administratively possible. Therefore, the team decided to implement the game *only* with bridging materials and full support in order to understand its potential.

Teachers who participated in the implementation study agreed to use *Zoombinis* in their classrooms, have regular conversations with an EdGE buddy assigned to help the teacher navigate the platform, complete weekly logs with open- and close-ended prompts, and participate in classroom observations. These teachers also consented to an exit interview with Knology researchers after completing other study requirements. When we refer to teacher who participated in the implementation study elsewhere in this report, we refer to teachers who had access to all of these resources.

As part of the study, EdGE considered multiple options for best reshaping the game to support both classroom and research needs, ultimately determining that building detectors into the game would allow both teachers and researchers to monitor student progress. EdGE first assessed these detectors for educational validity, which they determined required further study before expanding access to this observation tool for the teachers. Based on this need for research, EdGE eliminated the initial teacher dashboard concept and instead opted to further modify and refine how to collect data before making it available.

The EdGE team worked with the teachers to identify which of the game's puzzles would focus most clearly on the computational thinking constructs of interest, and developed bridging materials for the four games most suitable for these experiments. The puzzles most aligned to the project's goals were Pizza Pass, Allergic Cliff, Mudball Wall, and Bubblewonder Abyss. They ultimately developed detectors for the first three of these puzzles.

Evolution of Evaluation Plan

The original evaluation plan for the *Zoombinis* implementation research study included three phases: 1) A front-end study to assess teachers' needs and the best strategies for improving CT learning for a broad population with *Zoombinis*; 2) A formative phase focused on three case study sites that implemented the game throughout an entire school or district, rather than in single classes at teacher discretion; and 3) A summative evaluation intended to explore the broader impact that *Zoombinis* can have on four target audiences – students, teachers, parents, and informal educators. As the implementation study evolved so did the evaluation strategies, as outlined below.

Front-End Evaluation: Knology and EdGE planned to survey a representative sample of 1,500 parents and educators of elementary- and middle-school students to understand their *Zoombinis* implementation needs. This survey was designed to explore the educator context and how an educator dashboard might enable reporting learning outcomes as direct feedback from individual student or classroom game play. Due to challenges with obtaining the desired sample size for each audience type, we made the decision to recruit participants from the National Council of Teachers of Mathematics Annual Meeting and its mailing list of educators. A total of 220 educators from 39 states representing a range of school and learning environments responded to the survey.

The research team received valuable feedback from the teachers for developing an educator dashboard as well as feedback on best ways to introduce and promote the game to educators. For example, the front-end evaluation revealed that a dashboard would need to be linked to the assessment of CT learning outcomes for the results to be useful. The data also showed that game-related information intended for educators would require explicit direct links between *Zoombinis* puzzles and the CT concepts that could be learned. Following the front-end evaluation, *Zoombinis* game development was suspended for a short time because of a shift in responsibilities for game developers partnering with EdGE.

Formative Evaluation: While Knology originally planned to carry out the case studies as part of formative evaluation, there were logistical challenges associated with conducting the proposed case studies, namely securing IRB approval.

Due to the suspension of game development, it was not possible to complete formative evaluation. All formative activities were reimagined as summative evaluation.

Summative Evaluation – Educator Interviews and Student Game Play Assessments: Teachers who signed up for the implementation study were primarily individual teachers, not teachers in districts with broad adoption of *Zoombinis* in their systems. When activities resumed, the partners opted to shift the focus of the study away from broader implementation efforts to teachers' experience using the game and associated materials in classrooms. At the same time, EdGE recognized that teachers needed more support for implementation than previously believed and set up a buddy system to support teachers in this process.

The buddy system led to teachers in the study developing personal relationships with EdGE employees. Therefore, Knology researchers conducted exit interviews – which were originally planned to be led by the EdGE team – to ensure teachers felt comfortable giving honest feedback. In preparing for the teachers' exit interviews, Knology used information from teachers' logs of *Zoombinis* game play to develop tailored questions for the conversations.

Concurrent with the efforts to plan exit interviews, EdGE began considering evidence for and interest in CT as way of engaging broad and diverse ***learners*** rather than broad and diverse ***schools***. They began exploring the potential of CT learning to equalize the performance of neurodiverse students, that is students with neurological differences that impact how they learn. The most available proxy for neurodiversity in this study was the presence of either an Individualized Education Plan (IEP) or 504 plan (formal plans that schools develop to support students who need special accommodations to ensure academic success and full access to learning). However, we recognize that students have IEPs/504s for many reasons beyond neurodiversity and that not all neurodiverse students require similar accommodations. As a final evaluation study and to understand the potential effects of playing *Zoombinis* on different kinds of learners, Knology looked for evidence of differences in CT skills between students with and without IEP/504 status based on their game play. We judged their gameplay using an algorithm EdGE developed to classify student data from game logs for the three *Zoombinis* puzzles used in this study. Finally, we also looked for evidence of different ways to group learners other than using their IEP/504 status.

Front-End Evaluation: Educator Survey

Based on the results of a nationwide survey of educators, the front-end evaluation of *Zoombinis* describes the conditions and perceptions of educators who would consider using digital games to help their students' CT learning. The evaluation explored the educational context and how an educator dashboard might make it possible to report learning outcomes as direct feedback from individual student or classroom-level game play. Full results are available in the Front-End Survey Report (Shane-Simpson & Fraser, 2016). We summarize the main results in this section of the report.

Methods

Knology and EdGE developed a 35-question survey (Appendix A) that explored CT concepts taught by educators, perceptions of the *Zoombinis* game, how the game might be integrated effectively into curricula, and barriers to digital game use for student learning. The survey questions also covered access to technology in the classroom or other learning environments, and educator feedback on the utility of an Educator Dashboard and opportunities for additional support.

The survey began with screening questions that asked participants to note which **computational concepts** they cover in their teaching. If educators said that they did not engage in any CT concepts, the survey was subsequently terminated.

We explored educators' **perceptions of the *Zoombinis* game** by providing them with video clips of three *Zoombinis* puzzles games, and asking them to identify CT concepts (if any), and how strongly they were presented.

We asked educators if they would **incorporate *Zoombinis* into their curricula**, how they would use it, and how they felt their students would engage with it.

We assessed **barriers to digital game use** both from an educational and a personal standpoint. Items for this module were based on open-ended responses collected informally by EdGE.

One module focused on exploring **access to technology in the educational setting** by asking educators about students' access to technology, what types of technology students have access to, and when, where, and how often they have access. Items for this module were based on open-ended responses collected informally by EdGE.

We also gathered **educators' feedback on the utility of an educator dashboard**, including forms of student assessment that could be embedded within the dashboard. We also asked them about the value of support services including **professional development workshops** and access to a **community of fellow teachers** also using game-based learning approaches.

We used SPSS to conduct quantitative data analysis, including the descriptive statistics.

Participants

Participants were drawn from a list of over 20,000 attendees to the National Council of Teachers of Mathematics annual conference. Individuals on this list were solicited through emails and postcards to take the online survey. Simultaneously, members of the EdGE team used Twitter, Facebook, and emails to recruit teachers who had either participated in previous EdGE studies or expressed interest in *Zoombinis*.

In total 220 educators responded to the survey. These individuals represented 39 states around the U.S. with varying levels of teaching experience in various teaching environments. Respondents also represented a wide range of grade levels, spanning grades 4 to 12. For a full description of educator demographics see Shane-Simpson & Fraser (2016).

Results

Educators responded to questions about which of six core CT concepts they teach in their classrooms: Problem Decomposition, Algorithms and Procedures, Data Representation, and Generalization. We provided definitions of each concept to ensure teachers were answering the items comparably. Of these concepts, Problem Decomposition was the most frequently indicated, followed by Data Representation, Generalization, and then Algorithms and Procedures (Table 1).

Table 1. Percentage and count of participants teaching each CT concept.

CT Concept	Definition	*n* (%)
Problem Decomposition	Students break down a complex problem or system into simpler parts or chunks that are easier to understand.	204 (93%)
Data Representation	Students use and interpret multiple representations of data or information to organize, make meaning, and draw conclusions or solve problems.	183 (83%)
Generalization	Students apply common algorithms to a variety of problems, forming a solid set of practical approaches to problem solving.	177 (81%)
Algorithms & Procedures	Students identify and articulate a set of instructions for a specific problem or task (e.g., write a recipe or instructions for a task, design the processes for a computer program).	173 (79%)
Automation	Students predict/plan a series of ordered steps or sequences for feasible and efficient solutions.	144 (65%)
Abstraction / Formulation	Students identify and articulate general sets of algorithms or procedures that apply to various problem types or conditions (i.e., abstraction or formulation).	134 (61%)

Note: Educators could select all items that apply and they could also select the response *I don't teach any of these concepts*. Educators who said they did not teach these concepts were screened out of the survey.

Experience & Perceptions of *Zoombinis*

Educators were shown photographs and three short videos of *Zoombinis* game play, and then asked whether they had ever played *Zoombinis*. Most educators had never played *Zoombinis* (64%, n = 141), about a quarter had played as an adult (23%, n = 50), 5% (n=10) had played only as a child, and another 6% (n = 13) reported playing both in childhood and as an adult, and 2% (n = 5) were unsure. Prior game play did not predict any further answers.

After viewing the videos, participants were asked how well they felt the game covered each of the CT concepts. Participants could respond on a five-point scale ranging from Concept is Not Covered (0) to Concept Is Covered (4). Educators rated all concepts moderately (Table 2).

Table 2. Participants' perceptions of CT coverage in *Zoombinis*.

CT Concept	*M* (*SD*)	*n*
Problem Decomposition	2.75 (1.13)	120
Automation	2.63 (1.00)	116
Abstraction/Formulation	2.92 (.96)	116
Generalization	2.98 (1.00)	114
Algorithms & Procedures	2.67 (1.11)	113
Data Representation	2.68 (1.09)	112

Note: 220 participants provided responses; CT concept categories were not mutually exclusive.

Participants were also asked whether they could identify any concepts covered in the game that were not included in the CT categories provided. Small numbers of teachers suggested a range of additional skills, such as Problem Solving (n = 10), Perseverance (n = 7), Logic Skills (n = 5), and Collaboration/Cooperation (n = 3).

Including *Zoombinis* in the Classroom

We asked educators if they would use *Zoombinis* in their classroom. We note here that their responses were most likely based on a limited amount of information presented in the survey, and prior game play did not predict responses to this question.

Table 3. Teachers' responses to whether they would use *Zoombinis* with their students.

	n (%)
Yes	71 (51%)
No	35 (25%)
I don't know	32 (23%)

Note. n = 138.

Teachers chose various options when asked what strategies they might use to incorporate the game in their classrooms (Table 4). When asked how they felt their students would receive the game, the majority of the 132 respondents (n = 84) selected that their students would be actively interested in playing the game as part of the curriculum. As noted above, these answers are likely based on the limited amount of information about *Zoombinis* provided in the survey, as prior game play did not predict answers.

Table 4. Teacher-selected strategies for incorporating *Zoombinis* into their classrooms.

Teaching Strategies	*n* (%)
Have students play the game in class	73 (67%)
Use examples from the game in class	64 (59%)
Make *Zoombinis* assignments and / or activities	59 (54%)
Assign the game for out of class time	50 (46%)
Other	19 (17%)

Notes: A total of 109 teachers responded to this question. Teachers could select as many responses as were applicable.

Barriers to Use

We asked participants about barriers to digital games in general and specific barriers that they would anticipate in using *Zoombinis*. We grouped barriers into two areas: support or accessibility and time or experience. We asked about both sets of barriers in the school or learning environment as well as personally. In all cases, respondents were able to select multiple barriers.

When asked about support or accessibility barriers in the school/learning environment, the most frequent response was the cost of digital games (70%; *n* = 90), followed by a lack of technology resources (36%, *n* = 46; Table 5). Responses to personal barriers were similar.

Table 5. Greatest school/learning environment barriers related to support or accessibility.

Barriers in School or Learning Environment	*n* (%)
Cost of digital games	90 (70%)
Lack of technology resources	46 (36%)
Inability to access games because it is available only on the web	23 (18%)
Lack of support from administration	16 (12%)
Lack of parental support	16 (12%)
Other (e.g. game sites are blocked, lack of at home resources)	13 (10%)
There are no barriers	20 (16%)

Note. *n* = 129. Participants were allowed to select all that apply.

Concerning time or experience in the school/learning environment, the two most frequent responses were insufficient time (62%; *n* = 79) and difficulty finding games that fit the curriculum (59%; *n* = 76; Table 6). These were also the two most frequent personal barriers cited, although teachers were considerably more likely to say they had no personal barriers than no barriers in the school.

Table 6. Greatest school/learning environment barriers related to time or experience.

Barriers in School or Learning Environment	*n* (%)
Insufficient time	79 (62%)
Difficulty finding games that fit the curriculum	76 (59%)
Emphasis on standardized test scores	61 (48%)
Not sure where to find quality games	51 (40%)
Not sure how to integrate games	45 (35%)
Lack of familiarity with concepts covered in the game	38 (30%)
Hard to find quality professional development	26 (20%)
Lack of familiarity with technology	13 (10%)
Other (e.g. demonstration of learning, student lack of familiarity with tech)	8 (6%)
There are no barriers	9 (7%)

Note: *n* =128. Participants were allowed to select all that apply.

When asked about personal barriers, educators' responses were similar to those offered for perceived school/learning barriers.

Access to Technology

Educators were asked about their access to and ease of use of technology in the learning setting. They were asked about the types of devices students could access, device-per-student ratios, and how often students actually had access to devices (Table 7). Computers or tablets in school labs or libraries was the most commonly reported technology students have access to (Table 7). Nearly half of respondents said their students had 1:1 access to classroom computers, while a little over one-third said student to computer access is 4:1 or greater (Table 8).

Table 7. Technologies available to students.

Student Access to Devices	*n (%)*
Computers/tablets in labs or libraries	82 (68%)
Computers in the classroom/learning environment	81 (67%)
Computers/tablets after school or at home	64 (53%)
Tablets in the classroom/learning environment	50 (41%)

Note. *n* =121. Participants were allowed to select all that apply.

Table 8. Student-to-computer access ratios in the classroom/learning environment.

Ratio	*n (%)*
1:1 student to computer access	54 (44%)
2:1 student to computer access	15 (12%)
3:1 student to computer access	11 (9%)
More than 4:1 student to computer access	44 (35%)

Note. *n* = 124.

We asked participants how often their students have 1:1 computer access in their classroom/learning environment. Thirty-three percent (*n* = 41) of educators reported that students had 1:1 access every day, while 18% (*n* = 23) reported 2-3 times a week, 30% (*n* = 38) reported once a week, and 18% (*n* = 23) reported less than once a week.

We asked participants for the ratio of students to computer access in their lab or library (Table 9). Most participants indicated 1:1 access (75%, *n* = 90 out of 120), much higher than in classrooms, as reported above.

Table 9. Student-to-computer access ratios in the lab or library.

Ratio	*n (%)*
1:1 student to computer access	90 (75%)
2:1 student to computer access	8 (7%)
3:1 student to computer access	1 (1%)
More than 4:1 student to computer access	8 (7%)
Do not have a computer lab	13 (11%)

Note: *n* = 120. These results were not significantly related to the economic status of the students as indicated by the percentage of students qualifying for free or reduced cost lunch.

We asked how often students have 1:1 computer access in their lab or library. For access to computers in their lab or libraries, 30% (*n* = 36) of educators reported that students had a 1:1 ratio *once a week,* and the same number said *less than once a week,* 17% (*n* = 20) said every day, 12% *(n = 15)* said *2-3 times a week*, and 12% *(n* = 14) had no access to a lab or library.

We asked about the ratio of student to tablet access in the classroom/learning environment. Most participants reported access ratios of more than four students per tablet (Table 10).

Table 10. Student-to-tablet access ratios in classroom/learning environment.

Ratio	*n (%)*
1:1 student to tablet access	39 (36%)
2:1 student to tablet access	8 (7%)
3:1 student to tablet access	5 (5%)
More than 4:1 student to tablet access	55 (51%)

Note. *n* = 107.

Participants were asked how often their students had 1:1 access to tablets in the classroom. Many reported students having access to tablets less than once a week (54%, *n* = 58). Others reported access every day (19%, *n* = 21), 2-3 times a week (16%, *n* = 17), or once a week (11%, *n* = 12).

Lastly, when asked how often their students had 1:1 access to a computer or tablet after school or at home, almost half reported access every day (48%; *n* = 58), while smaller numbers reported access 2-3 times a week (12%; *n* = 15), once a week (2%; *n* = 3), less than once a week (6%; *n* = 7), or that they didn't know (31%; *n* =38).

Most participants (70%, *n* = 83) said that they didn't know about the ratio of student to tablet access after school/at home, while others reported varying access ratios (Table 11).

Table 11. Student to tablet ratio after school/at home.

Ratio	*n (%)*
1:1 student to tablet access	20 (17%)
2:1 student to tablet access	5 (4%)
3:1 student to tablet access	5 (4%)
More than 4:1 student to tablet access	5 (4%)
Don't know students' access	83 (70%)

Note. *n* = 118.

We asked educators what version of a game would be easiest to provide their students. The majority (73%; *n* = 76) indicated an Internet browser version (web-based). Others reported a tablet-based version (18%; *n* = 19), a desktop download (13%; *n* = 13), or selected other (i.e., iPhone, Android, need separate accounts for iPad).

Both desktop download (60%; *n* = 37) and tablet (55%; *n* = 36) were described as versions that educators wouldn't or couldn't use. Other restrictions on use included Internet browser (15%; *n* = 10) and other (6%; *n* = 4; i.e., laptops, java).

Developing an Educator Dashboard & Additional Support

Lastly, we asked educators if they felt an educator dashboard tool would be helpful moving forward. Creating a tool that provides feedback to educators about individual students' progress and the classroom as a whole is a long-term goal for EdGE. We asked teachers to rate which aspects of a teacher dashboard would be important, based on a list of choices. Teachers felt that receiving alerts/notifications about students' struggles, suggestions for interventions for those students, and STEM content alignment would be the most important aspects of a dashboard, should it be developed. They also suggested additional features, such as the ability to set goals/give badges, certificates of achievement, easy ways to add users, message board/chat functions, and offering parental access to student progress.

Finally, teachers were asked if additional support services would influence their decision to use (or continue using) game-based learning. Rating these from a list of choices, participants expressed the most interest in the online tool (dashboard) for viewing and monitoring students' gameplay, access to educator-developed/reviewed curriculum materials that support game-based learning, and a single location to find high quality educator-reviewed STEM games.

Summative Evaluation: Educator Exit Interviews

The final structure of the implementation study offered ample scaffolds for the teachers who participated. These teachers agreed to use the *Zoombinis* game and bridging materials in their classrooms, hold regular conversations with an EdGE buddy, fill out weekly logs with open- and close-ended prompts, and participate in classroom observations. They also consented to an exit interview with Knology researchers after completing other study requirements.

Knology researchers conducted exit interviews with almost all of the participating educators, and conducted a secondary analysis of all teacher logs to prepare more specific interview questions. We reviewed the learning dynamics associated with gameplay by considering educators' logs of in-class *Zoombinis* activity, how frequently specific puzzles were used, and educators' assessments of student achievement.

In general, teachers responded positively to *Zoombinis* and agreed that gameplay effectively incorporated CT concepts and principles in their classrooms. Teachers had different levels of comfort with CT concepts and varied in their capacity to promulgate these concepts to their students and across disciplines. They felt that the game was appropriate for a broad range of students but noted some mediating effects related to age, gaming experience, special education or IEP status, and English learner designation (cf. Rosa, 2019, p.6 n.12 on the need to simultaneously de-naturalize this designation and recognize its effects).

Methods

Two Knology researchers participated in each interview — one leading the conversation and the other taking notes. We used a semi-structured exit interview protocol to follow up on the teacher logs and address the research questions in this chapter. In addition to the questions we asked of all teachers, Knology researchers used information from teacher logs to prepare several tailored interview questions for each interviewee (see Appendix B for the interview protocol).

Participants

Knology interviewed all educators who completed participation in the broader *Zoombinis* implementation study. After teachers completed all other requirements, an EdGE staff member introduced the Knology team to the teacher. In total, we conducted 36 interviews. All were recorded, except for two where there were technical difficulties. Several additional teachers agreed to participate but ultimately dropped out; these teachers were not interviewed.

In this and previous reports, we used the terms *teacher*, *educator*, and *instructor* interchangeably in recognition of the varied roles that educators play. We also used the singular *they* to refer to all participants to preserve confidentiality.

Using data from the logs, the evaluation team grouped teachers by grade level although many of the teachers who consented to be interviewed actually teach multiple grades. Several teachers teach multiple subjects, with the bulk of interviewees reporting their subject matter as "general" (Table 12). Relevant to the subject of the implementation study, four teachers listed their subject matter as computer science or coding. Teachers indicated their students had varying levels of access to computers.

Table 12. Number of teachers who taught each subject area.

Subject Matter	*n*
General (i.e. classroom teacher)	13
Technology	7
Math	4
Computer science or coding	4
Science	3
Combined math and science	1
Other*	10

Note: Several teachers taught multiple subjects. **Other* classes included robotics, engineering, and STEM (n = 4); unspecified electives (n = 2); art and technology (n = 1); critical thinking (n = 1); information processing (n = 1); and Scratch (n = 1).

Most teachers tried all of the *Zoombinis* activities at least once, but some puzzles were more popular than others. Nearly all teachers used Allergic Cliffs, Pizza Pass, and Mudball Wall. Slightly fewer teachers used Bubblewonder Abyss and just a handful used *Zoombinis* Scratch and other miscellaneous activities not part of the core research focus. Teachers typically used one puzzle more than the others: 13 teachers used Allergic Cliffs more than any other puzzle, while 11 favored Pizza Pass, and 11 favored Mudball Wall. These numbers include the 10 teachers who used between two and four activities an equal number of times.

Analysis

Two Knology researchers coded the same six interviews individually to develop an evidence framework (Appendix C). After discussing the coding scheme, the researchers attained consensus about the framework and then divided the remaining 30 interviews for analysis.

The research team considered three levels of CT understanding that could occur for both teachers and students. We defined *implicit* understanding as being able to complete a task but not necessarily explain it. *Explicit* understanding of CT skills refers to being able to verbally explain the skills used to complete a task. The third level looks at the *transfer* of CT skills to other content areas. These levels build on each other, with each successive level requiring mastery of the prior levels. Our team coded for teachers' understanding of CT as well as teachers' reflections on students' ability (Table 13).

Table 13. Evidence of levels of teacher and student understanding of CT.

Level of Understanding	Evidence in teachers	Evidence in students, as perceived by teachers
Implicit	Teachers mentioned teaching gameplay directly or treated gameplay as the end goal.	Teachers said gameplay or game success was their only evidence of student learning.
Explicit	Teachers used gameplay to segue into discussions about CT and / or other computer skills.	Teachers reported student use of CT terms to describe gameplay.
Transfer	Teachers explicitly treated CT as a problem-solving methodology, drawing connections to topics / disciplines beyond computer science or coding.	Teachers reported students applying skills in new contexts or subjects.

The final evidence framework focused on the following themes. All themes are described in Appendix C.

- Teacher guidance about CT (implicit, explicit, and/or transfer to other areas);
- Student CT achievement (implicit, explicit, and/or transfer to other areas);
- Instructional strategies;
- Use of the four CT terms (problem decomposition, pattern recognition, abstraction, and algorithm design);
- Barriers and supports to implementation including interaction with EdGE buddies;
- Differences between student populations; and
- Changes in teacher understanding of CT.

Results

Implicit & Explicit Understanding of Computational Thinking

Most teachers reported using Zoombinis gameplay as a lead-in to teach CT, rather than as the endpoint of CT instruction. Furthermore, most teachers (n = 24 out of 36) could articulate how CT skills could transfer to other subject or skill areas. Of the subset of teachers that engaged in transfer, some focused on skills transfer to a single subject while others explored transfer to multiple disciplines.

Some participating educators taught computer science or technology and were easily able to connect CT skills with their subject matter. But these teachers had a harder time connecting CT to other curriculum areas. A few teachers (n = 10) stopped at explicit understanding of CT in their classrooms. That is, they were able to describe how they articulated CT skills to their students but unable to make connections between CT and other subject areas.

Most teachers saw gains in both explicit learning and skills transfer in their students. Of the educators interviewed, four teachers reported observing only implicit understanding, based on seeing students' progress through puzzles more quickly with repeated attempts. Other teachers who were interviewed were split fairly equally between those who saw explicit learning — students able to verbally articulate the CT skills that they were learning — and those who saw students use the vocabulary associated with CT in other subjects. Many teachers reported a range of levels of CT skills present in their classrooms and non-uniform progress across students and activities. Other teachers noted improvements in math and science skills but were unsure if these could be attributed directly to playing *Zoombinis*.

Educators tried both individual and group-based strategies to help students move from implicit to a more explicit understanding of CT. Teachers also incorporated *Zoombinis* into their class routines in different ways. Some teachers let students play *Zoombinis* during unstructured free time while others used the game as part of structured lesson plans. They also offered opportunities for students who grasped *Zoombinis* concepts quicker to teach gameplay strategies to their peers. This peer-to-peer teaching approach proved beneficial for some students who were struggling and contributed to a more uniform level of understanding in the class, according to the feedback from the educators.

Thirty-two teachers reported using non-game bridging activities including charts, data tables, posters, walkthrough strategy videos, and Google slides to teach CT skills. More than half of the respondents customized the activities in some way including:

- Adapting EdGE's hands-on activities to work with Legos;
- Developing a taxonomy activity using *Zoombinis* cards;
- Using Zoombinis characters in other classes such as English and social studies;
- Setting up scenarios that required students to categorize one another and respond to prompts based on physical attributes such as hairstyle and clothing;
- Asking students to use attributes to describe rocks;
- Creating more collaborative versions of worksheets;
- Providing journals for students to record reflections;
- Encouraging competition between students in the game's story mode; and
- Writing additional discussion prompts.

Broad & Equitable Improvement of Computational Thinking

One objective of the *Zoombinis* implementation study was to ensure broad and equitable improvement of CT learning in classrooms. Teachers reported that a broad spectrum of students found the game engaging but there was some uncertainty about the degree to which students learned CT concepts. Most teachers saw improvements in their students that they attributed to gameplay but could not say which groups benefitted the most. Some teachers identified specific groups which showed differences in learning by age; gaming experience; special education, learning disabilities, and individualized education programs (IEPs); and English language learners (ELLs). However, there was no uniform answer from all teachers on who can benefit the most from the game.

Several teachers felt that *Zoombinis* would be more engaging for elementary school students rather than for middle school students. The effects of prior gaming experience on student engagement was mixed — some non-gaming students were uninterested in the game, while some regular gamers had a hard time learning to play.

Teachers of special education students and students enrolled in IEPs reported that most of these students did as well or better with *Zoombinis* when compared to other types of activities. Several teachers noted the mostly positive effects of the game for students they identified as being on the autism spectrum.

ELL students also did well with *Zoombinis* possibly due to the absence of a language barrier in gameplay, according to teachers. The game also afforded these teachers a new way to assess ELL students' learning.

Teachers' Understanding of CT Principles

We assessed educators' own understanding of the four facets of computational thinking. Their responses revealed that prior to participating in the *Zoombinis* study, teachers varied in terms of their levels of experience with and understanding of CT. Seven teachers mentioned that they had taught CT before participating in the study, and three of these teachers noted that they had been less explicit about the subject in previous teaching experiences. Ten educators had used *Zoombinis* before, but many of these teachers also said that they were previously unfamiliar with CT concepts and vocabulary.

Both teachers' self-reports and our analysis of teachers' definitions of CT indicate that overall the educators' understanding of CT improved. Twenty-six teachers expressed a high level of confidence with CT terms and concepts following their participation. This result also held true for teachers who had taught CT before the study.

The biggest shift that researchers observed was in teachers' pre- and post-study definitions of the four CT facets — pattern recognition, problem decomposition, abstraction, and algorithm design. For example, one teacher who initially gave a broad definition about problem-solving defined CT in their exit interview as *"the strategies you need to solve a problem using things like decomposition, abstraction, pattern recognition, etc."* We note that only two teachers said that they didn't understand and felt uncomfortable with teaching and explaining CT concepts during interviews.

Many teachers said that they used all four CT facets comfortably with students and reported teaching all four to varying degrees. Teachers typically said that pattern recognition and problem decomposition were the most valuable or important topics. Fewer teachers identified abstraction and algorithm design as equally important. Teacher logs showed that all teachers taught problem decomposition and pattern recognition at least once (Table 14), while several teachers did not teach abstraction or algorithm design.

Table 14. Number of teachers who taught each CT skill at least once.

Skill	*n*
Problem Decomposition	36
Pattern Recognition	36
Algorithm Design	32
Abstraction	29
Other	13

Notes: Teachers could select all items that applied. Nearly all teachers taught all CT skills.

Teachers were more likely to focus on problem decomposition and pattern recognition, and no teachers reported spending the most time on abstraction. Very few teachers reported spending the most time algorithmic design (Table 15).

Table 15: Number of teachers who taught each CT skill most frequently.

Skill	*n*
Pattern Recognition	20
Problem Decomposition	17
Algorithm Design	4
Abstraction	0
Other	0

Note: Five teachers taught two or more CT skills on an equal number of occasions.

Less than half of the educators interviewed (*n* = 14) included CT in their formal curriculum while a handful (*n* = 4) treated the subject as an unstructured activity. Unsurprisingly, computer science teachers had an easier time connecting *Zoombinis* to their curriculum, and in many cases had used other computational thinking-focused programs in their classrooms. The challenge for these teachers was connecting concepts to subject areas outside of the computational domain. Other teachers reported that the study had helped them connect the four facets in new ways and enabled them teach CT in a more unified way.

Support from EdGE Buddies & Other Teachers

The responses to the EdGE buddies was largely positive. Twenty-six teachers spoke well of their relationship, five had mixed feelings about the partnership, and two were somewhat negative.

Teachers also showed considerable independence in the way they sought support in using *Zoombinis*. Many teachers noted that they primarily asked for help from teachers they knew or from members of the teacher Google group since these individuals' experiences with *Zoombinis* were more directly relevant to their own.

Barriers to Implementing *Zoombinis*

In interviews, teachers explained experiencing some of the same barriers that were anticipated by educators in the front-end study:

- Bureaucratic challenges at the school or district level;
- School cancellations which disrupted teaching flow;
- Time constraints that made it difficult to implement and teach *Zoombinis*;
- Differences in standards that made it hard to implement activities consistently across classrooms;
- A lack of resources at the school or district level;
- Teachers' general unfamiliarity with gaming or with *Zoombinis* in particular; and
- Language barriers for students designated as English learners.

Teacher Recommendations for Enhancements

We organized teachers' suggestions for improving *Zoombinis* into four categories:

Accessibility

- Teachers were excited about a smart phone version of *Zoombinis* that could allow more students to play the game at home;
- Teachers requested more consistency between English and Spanish language instructions; and
- Teachers asked for translations of instructions into other languages.

Tutorials and teacher resources

- Teachers requested a simplified tutorial video for at least one puzzle and instructional videos for some of the higher levels of puzzles; and
- Teachers asked for an educator dashboard that offers more visibility into student activities within the game.

Cross-curricular application

- Teachers asked for more targeted bridging activities that connect CT concepts to humanities and social science subjects; and
- Teachers also requested a mapping between CT and state standards across all subject areas.

Teacher community of practice

- Teachers asked for more mentorship and communication with other teachers implementing *Zoombinis*;
- Teachers asked for support for team teaching; and
- Teachers also asked for more online interaction with peers and connections to other teachers who could discuss the experience of implementing the game in a classroom.

Summative Evaluation: Assessment of Student Game Play

Over the course of the project, EdGE began considering evidence for and interest in CT as way of engaging broad and diverse ***learners*** rather than broad and diverse ***schools***. They began exploring the potential of CT learning to equalize the performance of neurodiverse students, that is students with neurological differences that impact how they learn. The most available proxy for neurodiversity in this study was the presence of either an IEP or 504 plan. As a final evaluation study and to understand the potential effects of playing *Zoombinis* for different kinds of learners, Knology looked for evidence of differences in CT skills between students with and without IEP/504 plans based on their game play. We judged their gameplay using an algorithm EdGE developed to classify student data from game logs for the three *Zoombinis* puzzles used in this study.

Methods

EdGE collected teacher ratings of students' CT skills and of how the students' CT learning compared to other academic activities. EdGE also recorded game play activity in game logs. The game play activities were algorithmically classified into categories of computational thinking and skills. The detectors classify phases of problem solving (such as trial and error or systematic testing), computational thinking facets, gameplay efficiency, and strategies specific to each puzzle (Rowe et al., 2018; Rowe et al., in review).

Participants

EdGE collected data from 374 students in third through eighth grades. Of the total number of students, 82 were excluded from the analysis because of missing data on the two factors relevant for testing: IEP/504 status and grade level. All the analyses reported in the following sections were run on the data from the remaining 292 students. This final sample included 129 students from grades 3-5, of which eight had IEP/504 plans, and 163 students from grades 6-8, of which 49 had IEP/504 plans.

Analysis

We conducted two complex statistical analyses of the data. For ease of reading, we include analytic methods in each section.

Study 1: Comparing CT Learning to Other Academic Activities

After reports from teachers (see previous chapter) suggested that Zoombinis and the associated CT curriculum might equalize performance between students who have IEP/504 plans and those who do not, we examined the relationship between students' IEP/504 status and teachers' assessment of students' CT learning compared to other academic activities. Teachers reported no change in the six students with IEP/504 plans in grades 3 – 5 (Lower). For the 26 students with IEP/504 plans in grades 6 – 8 (Upper), teachers reported better performance for most students and worse performance for a small number of those students (Table 16). This would appear to indicate that teacher assessments are unrelated to whether students have an IEP/504 plan.

Table 16. Relationship between students' status and teachers' assessment of CT learning compared to other activities.

		Performance		
School Level	IEP / 504	Better	No Change	Worse
Lower	No	35	63	9
Lower	Yes	0	6	0
Upper	No	40	38	2
Upper	Yes	17	6	3

Note. We did not receive teacher assessments for all students from whom we have game play data, thus $n = 219$ rather than the full 292. Lower represents grades 3-5, and Upper represents grades 6-8. Teachers were first asked to rate the extent to which they saw each CT component in each student's work. This chart reports on a follow-up question, *How do these CT ratings compare to this student's typical academic performance in other classroom activities?*

To corroborate this seeming equalization of different types of students, we used ordinal logistic regression to model how students' CT learning compared to other academic activities (rated as Better, No Change, and Worse). We tested the relationship of this teacher comparison to whether students have an IEP/504 plan and whether students were enrolled in grades 3-5 or grades 6-8. Additionally, we controlled for three two ground-truth indicators—one of student motivation and two of student performance:

- A summary variable derived from the detectors of game play; and
- A summary variable derived from the teachers' assessments of four CT facets (Problem Decomposition, Pattern Recognition, Abstraction, and Algorithm Design) summarized as a single PCA component.

The ordinal logistic regression model fails to offer evidence that teachers differentially assess students with and without IEP/504 plans. School level (lower vs. upper) and the summary score for the four CT facets assessed by teachers were the only reliable predictor for the teachers' comparative assessment of student performance. The latter result suggests that teachers were self-consistent in their assessments. See Appendix D for full results.

Study 2: Relationship between Implicit CT Skills & IEP Status

Students' game play offers an opportunity to explore the extent to which CT learning equalizes the performance of students with and without IEP/504 plans. To explore this question, we looked at game logs for three *Zoombinis* puzzles: Pizza Pass, Mudball Wall, and Allergic Cliffs. Student game behaviors were classified by algorithmic detectors into probabilistic instances of several aspects of CT. Our analyses use classifications data for common detectors across the three puzzles: Abstraction, Pattern Recognition, Problem Decomposition, and Algorithm Design.

We used Discriminant Function Analysis (DFA) to see if detector classifications could predict IEP/504 status. DFA tests the extent to which the distribution of a quantitative variable differs relative to a qualitative variable. Here, we tested the extent to which the distribution of probabilistic detector classifications (averaged by player) differs relative to IEP/504 status.

Two of the four classification detectors—Pattern Recognition and Algorithm Design—exhibit statistical (p values < 0.05) but not substantive (correlation ratios $\ll 0.20$) reliabilities in predicting IEP/504 status. Full statistical results are available in Appendix D. Figure 3 shows how the distributions of these statistically reliable detector classifications differ by IEP/504 status.

Students with and without IEP/504 plans exhibited differences in CT skills, but these differences were small and hard to discern (with overlapping distributions). Consequently, it was easy to misclassify students with or without IEP/504 plans using their game play alone. In fact, of the 57 students with IEP/504 status in both lower and upper grade levels, 56 were miscategorized by the DFA model based on the detector data. This lack of clearly differentiated CT skills may indicate that CT learning equalizes the performance of students with and without IEP/504 plans.

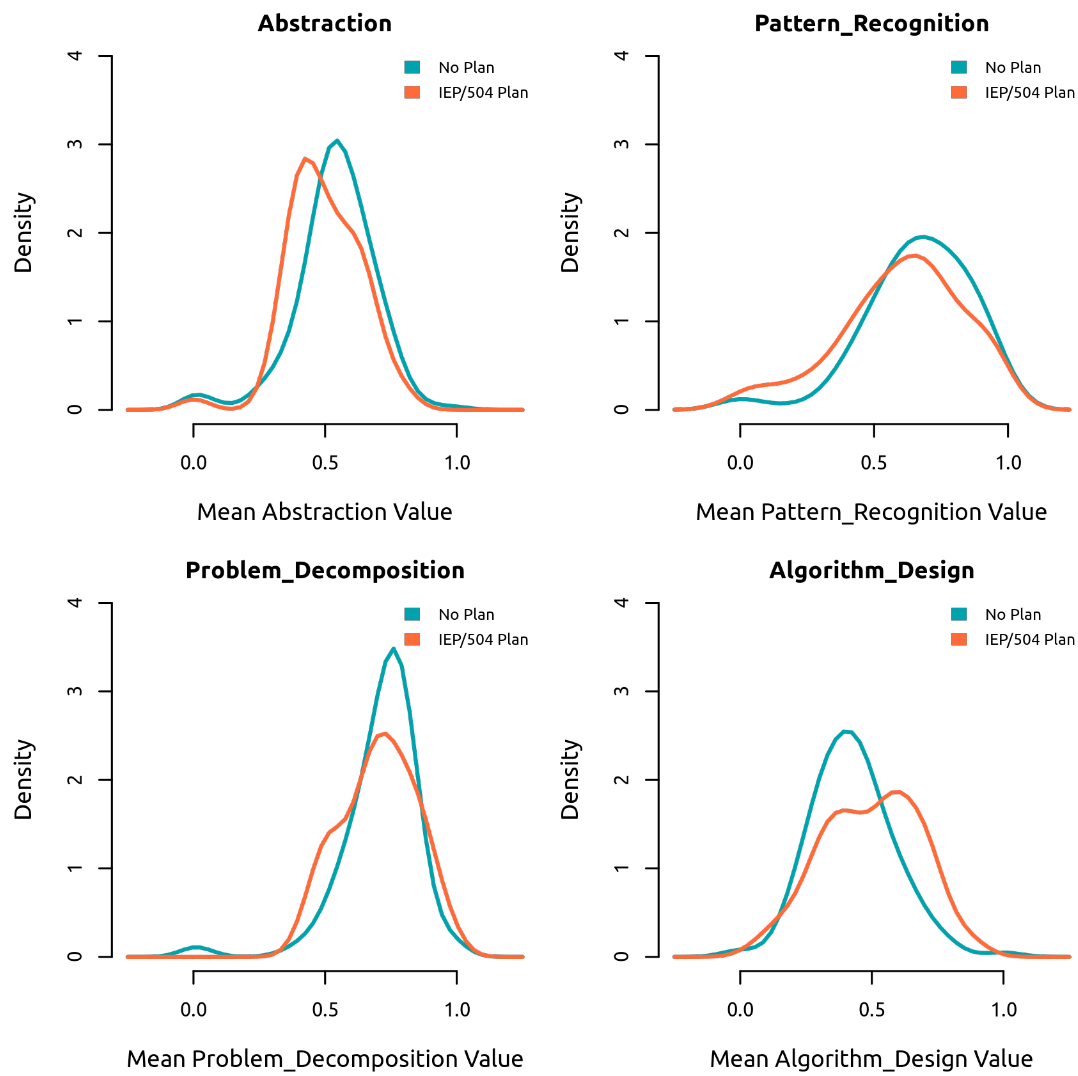

Figure 3. Density plots for probabilities of the detector classifications by IEP/504 status.

Discussion

The evaluation of the *Zoombinis* implementation study highlighted several important benefits of playing the game in the classroom for both students and teachers and indicated several new research directions. Key among these benefits is the game's adaptability to different contexts and settings. Specifically, teachers in the study felt that *Zoombinis* was an effective teaching tool for a wide range of students, although they observed some differences that may have an impact on learning outcomes. Most teachers who implemented the game were generally able to incorporate the experience into their own curriculum and classroom structure. And most saw high levels of student engagement with the game as well as increased understanding and transfer of CT concepts to other areas.

To demonstrate the gains made over the four-year study and highlight future research potential, we have structured this discussion around the research questions. Each section includes a brief description of our findings and then places those findings in a broader context.

Evidence of Implicit CT

The evidence for students' implicit CT learning in Zoombinis comes from EdGE's work (e.g. Rowe, et al., 2018). Through a combination of hand-labeling playback data and data mining, they developed a series of algorithmic detectors that serve as game-based learning assessments. For example, the detectors for one puzzle, Pizza Pass, can now identify:

- Four iterative phases of problem-solving:
  - Trial & error,
  - Systematic testing,
  - Systematic testing with partial solution, and
  - Implementing full solution;
- Three of the four facets of computational thinking:
  - Problem decomposition,
  - Pattern recognition, and
  - Abstraction; and
- Three problem-solving strategies:
  - One-at-a-time testing;
  - Additive testing; and
  - Subtractive testing, or winnowing.

Evidence for the facets of computational thinking comes particularly from the problem-solving strategies. Using the same strategy consistently in one game round is evidence of problem decomposition, while using the same strategy across multiple game rounds is evidence of algorithm design.

From Implicit Knowledge to Explicit Learning & Transfer

We identified three levels of CT understanding in both teachers and students. *Implicit* understanding is the ability to complete a task, while *explicit* understanding is the ability to verbally explain the skills and process. Finally, *transfer* includes using the skills in novel contexts or disciplines.

For teachers to identify students' implicit knowledge and leverage it for explicit learning, they themselves needed a strong understanding of CT concepts. Teacher interviews showed that about three-quarters of participating teachers were comfortable with CT concepts and vocabulary after participating in the *Zoombinis* study, although most of them had been unfamiliar with these concepts before their participation. In particular, teachers who gave broad pre-study definitions of CT largely couched their post-study definitions in the four featured facets, suggesting an increase in comfort with the subject. Of the four featured facets, teachers struggled most with abstraction.

Most teachers used the game as a starting point to teach CT ***explicitly*** and make connections to other computer skills. In interviews, about two-thirds of teachers also articulated ways that CT could ***transfer*** to other disciplines. Of this group of teachers, some focused on exploring how CT skills transfer to a single subject, while others drew connections between CT skills and multiple disciplines in their classrooms.

While teachers used a wide range of instructional strategies, the majority used offline activities to support explicit learning. EdGE provided various offline resources including cards, worksheets, and slides. For many teachers, offline activities were important because they allowed for alternative forms of assessment besides game success. Several teachers reported adapting some of the resources EdGE provided in different ways in their classrooms. Empowering students to help one another or explain tasks and strategies to the class was another important instructional strategy, because it required students to verbalize what they had learned.

Teachers had a variety of ways to teaching with CT. Unsurprisingly, computer teachers had the easiest time fitting *Zoombinis* into their curriculum and recognizing it as connecting to standards. About half of teachers used *Zoombinis* as a stand-alone activity and then did not make explicit connections for students to much of their 'normal curricular' content. However, teachers reported using the game in a lot of different ways in their classrooms, including individual, pair, group, and full-class play, which is a testament to its flexibility.

Many teachers saw students' use of CT vocabulary as one of the clearest indications of explicit learning. However, it is unclear if vocabulary use is the best or only proxy for explicit learning. Also, some teachers noted that their students struggled to use CT vocabulary for more difficult *Zoombinis* activities.

Broad & Equitable Improvement

Teachers in the implementation study typically found that *Zoombinis* was ***engaging*** for most of their students. However, they did not report uniform ***progress*** across students and activities. Educators identified prior gaming experience (cf. Fraser, Shane-Simpson, & Asbell-Clarke, 2014; Voiklis & Corter, 2012), age, special education or IEP status, and English learner designation as variables that led to variation in learning outcomes.

Age

Regarding applicability to learners of different ages, several teachers said that they felt that Zoombinis would be more engaging or effective for elementary school students rather than for middle school children. However, teachers saw more positive change in middle-school students than elementary-schoolers. But teachers also noted that puzzles varied in difficulty and students struggled with some puzzles more than others. Specifically, they felt that puzzles such as BubbleWonder Abyss were more difficult because students had to try multiple variables and conditionals at the same time to succeed.

IEP/504 Status

Over the four years of the project, the team has given considerable thought to the affordances of *Zoombinis* for "leveling the field" for different types of students. The EdGE team has found that *Zoombinis* appears to be more effective in improving computational thinking in girls than boys (Rowe, Asbell-Clarke, & Almeda, 2019; Elizabeth Rowe, personal communication). Multiple statistical analyses could not differentiate students with and without IEP/504 plans using EdGE's detectors. That is, students with and without IEP/504 plans played the game in similar ways, and teachers' assessments of performance and learning did not differ based on IEP/504 status. Together, these findings suggest that CT learning, and specifically *Zoombinis*, is broadly useful for creating equity in classroom learning. Teachers suggested that the wide range of puzzle structures, and the variable difficulty levels within each puzzle, gave them the opportunity to create challenges suited to students of a range of ages and abilities. The lack of explicit instructions in any language was seen as an advantage for both students designated as English learners and neurodiverse students, since performance does not depend on language skills or executive control.

When discussing the positive learning outcomes for students irrespective of IEP/504 status, teachers claimed in interviews that student game success was a useful proxy for learning, particularly at higher difficulty levels. That is, they believed that students could not complete harder levels purely by luck, and thus success was evidence of learning.

We caution that the study included only small numbers of students with IEP/504 plans. While we verified that the sample excluded so-called "gifted" students, the particular needs of students who had learning support plans were not specified. We cannot assure that the included students represented a broad range either of learning needs or of supports necessary to accommodate all students. Thus, neurodiversity appears to be a particularly promising and much needed avenue for further research. That research would require a larger and fully specified sample of neurodiverse students, rather than using IEP/504 plans as a proxy and not differentiating between variations in learning needs.

Games in the Classroom: 2015 and 2019

Our 2015 front-end survey, found a number of barriers to implementing Zoombinis and other game-based learning in the classroom: the cost of games, concerns about ties to curriculum, insufficient numbers of computers in the classroom, and difficulty of installing software. In 2019, as this project came to a close, the technological barriers identified in the earlier studies are impacting fewer and fewer schools. Some states now have CT or tech standards, making it easier for teachers to justify the time spent on games in the classroom. Many of teachers we interviewed had access to either Chromebook/laptop carts or 1: 1 access opportunities for their students. While time, cost, and other equity barriers highlighted in the initial survey may still be present across the US, overcoming these issues was not the focus of this research.

The Future of Computational Thinking

The definition of CT has solidified in the intervening years since the grant was written through the efforts of groups such as the International Society for Technology in Education. Simultaneously, EdGE has worked closely with teachers to identify the CT skills that are most clearly present in *Zoombinis* and transferrable to other activities. While the original *Zoombinis* proposal focused on six CT constructs – formulation, organization, automation, representation, implementation, and generalization – the final effort centered four focal constructs arranged in a loose learning progression: problem decomposition, pattern recognition, abstraction, and algorithm design. The team also recognize a behavior progression from trial and error, through systematic testing, to a working solution, then a full solution, and finally a general solution (Figure 4). This more nuanced understanding of process builds on the original set of constructs by distinguishing *phases of problem solving* (bottom row) from *competencies* (top row).

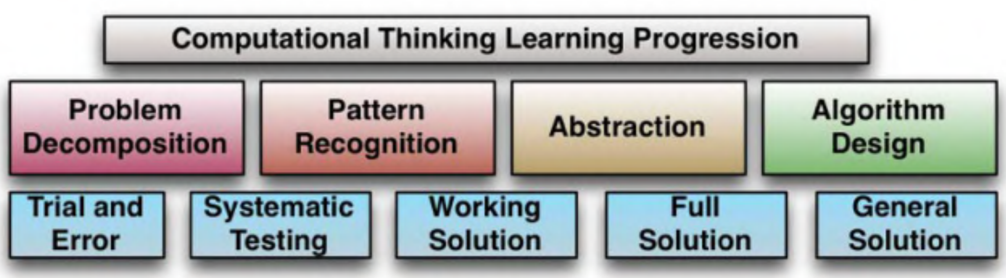

Figure 4. An iterative learning progression of CT that is operationalized in *Zoombinis* gameplay.

Note. Reprinted from Rowe, Asbell-Clarke, Gasca, & Cunningham (2017) with permission.

At the conclusion of the project, the team currently defined CT as *"the conceptual foundation required to solve problems effectively and efficiently (i.e. algorithmically, with or without the assistance of computers) with solutions that are reusable in different contexts"* (Shute, et al., 2017, p. 151). The EdGE team, along with members of the Knology evaluation team and leaders at Braintree Public Schools, has concurrently developed a larger learning progression that connects CT to the rest of the curriculum (Asbell-Clarke et al, ms.). In this progression, learners are first introduced to the concepts and vocabulary in upper elementary school. In early middle school, they explore various computational tools, such as 3D printing and block coding, in preparation to apply those tools across subject areas in upper middle school.

One working hypothesis explored by the EdGE and Knology teams locates the promise of CT in explicit metacognition. Kuhn (1999; 2000; Kuhn & Dean, 2004) has argued that critical thinking is fundamentally metacognitive, and we extend this argument to CT. In particular, we suggest that CT supports a particular type of metacognition: *metastrategic knowing,* or "meta-knowing about procedural knowing" (Kuhn, 2000, p. 179). Teachers suggested in interviews that the CT facets give them language to talk about thinking processes they would previously leave implicit, which aligns with this framework. In one study, explicit instruction in metastrategic knowing was particularly valuable for low-achieving students (Zohar & Peled, 2008), since many learners do not intuitively grasp these processes (cf. Kuhn 1999, 2000). Kuhn (1999, p.17) notes that *"the most pressing practical issue in current efforts to teach critical thinking [is] the fact that gains most often do not generalize beyond the immediate instructional context."* Teachers' and students' ability to transfer CT beyond gameplay and computer skills is evidence of its success, and suggests that drawing these theoretical connections is a promising avenue for future research.

Conclusion

Summative evaluation results reveal new potential for *Zoombinis* to help different kinds of learners grasp and apply computational thinking concepts. We found evidence that *Zoombinis* helps students gain both implicit and explicit learning of CT skills, as well as the ability to transfer those skills to other disciplines and aspects of life. Teachers also said that they found the final versions of the bridge materials to be useful and supportive. Most teachers involved in the implementation study said that they would continue to use *Zoombinis* in the future. Furthermore, teachers who had used the game prior to participating in the study said that their involvement has changed the way they use the game. Finally, the study suggests that the benefits of *Zoombinis* game play accrue similarly to learners with and without IEPs or 504 plans. In combination, these findings suggest that *Zoombinis* is a valuable educational option that can support broad and equitable improvement in CT skills.

Most educators said they felt comfortable incorporating *Zoombinis* and using it effectively in their classrooms. For the most part, teachers said their own understanding of CT improved through participation in the project, and that they felt equipped to guide students' own learning using the game.

The findings reported here and in earlier evaluation reports (Shane-Simpson & Fraser, 2016; Barchas-Lichtenstein, et al., 2018), suggest future directions for research. Early research in this domain shows that the game is effective at teaching CT skills for a range of learners but there is room to dig deeper. In particular, further study of neurodiverse students that differentiates specific learning needs is a necessary next step. For example, diagnostic information and/or information about specific accommodations would help disaggregate among this population.

The evaluation indicates that the National Science Foundation's support *Zoombinis: The Implementation Research Study of a Computational Thinking Game for Upper Elementary and Middle School Learners* produced a set of learning products that met the goals of the project. These products benefit both educator and student engagement with CT, as well as increase equitable improvement in this area of learning. This project has contributed to primary research and scholarly literature on CT learning and measurement. Finally, it has suggested avenues for new research to advance CT learning in the U.S.

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