Supporting Diverse Learners in K-8 Computational Thinking with TIPP&SEE

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ABSTRACT

With the growth of Computer Science (CS) and Computational Thinking (CT) instruction in the primary/elementary domain, it is important that such instruction supports diverse learners. Four categories of students – students in poverty, multi-lingual students, students with disabilities, and students who have below-grade-level proficiency in reading and math, may face academic challenges that can hinder their learning in CS/CT curricula. However, little is known about how to support these students in CS/CT instruction, especially at this young age. TIPP&SEE, a meta-cognitive strategy that scaffolds learning by proceduralizing engagement through example code, may offer some support. A quasi-experimental study revealed that the gaps between students with and without academic challenges narrowed when using the TIPP&SEE strategy, indicating its promise in providing equitable learning opportunities in CS/CT.

KEYWORDS

learning strategy, computational thinking, Scratch, elementary/primary education

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1 INTRODUCTION

An important goal of the Computer Science for All initiative in the US and similar initiatives worldwide is to diversify the CS workforce which is historically and disproportionately white and male to include women, people of color, those who are multi-lingual, and people with disabilities. While not all students will become future computer scientists, it is imperative that all students have equitable opportunities for learning to code and develop expertise in using technology, important aspects of quality of life and participatory citizenship in today's world.

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A prior study has shown that students using the TIPP&SEE learning strategy vastly out-performed students who did not [38]. *TIPP* stands for Title, Instructions, Purpose, and Play, while *SEE* stands for Sprites, Events, and Explore. The goal of this study is to see if TIPP&SEE was truly effective for all learners, not just students who have academic and/or economic advantages. Our objectives were two-fold: (1) to examine the relationships between learner characteristics and computer science learning at the primary/elementary level, and (2) to explore meta-cognitive strategy instruction as a method for providing equitable access to high quality CS/CT curricula with positive learning outcomes for all students, including diverse learners. It is only through research like this that traditionally underrepresented and marginalized students and those from under-resourced schools will experience accessible and equitable opportunities in school-based CS/CT. We are motivated by the following research questions:

- To what extent does the meta-cognitive strategy TIPP&SEE support diverse learners in CS/CT instruction?
- In which CS/CT concepts are diverse learners supported by TIPP&SEE?

In the next section, we detail the theories that ground our research. We follow it with an overview of related works in §3. Our methods are described in §4 and results in §5. We further discuss our findings and implications in §6. Lastly, we outline the limitations of this study in §7.

2 THEORETICAL FRAMEWORK

The design of TIPP&SEE was grounded in theories of meta-cognition more broadly and in the underlying cognition behind reading comprehension more specifically.

2.1 Meta-cognition

Meta-cognition involves both self-regulation in learning and motivational aspects of learning. People who are meta-cognitive are reflective and constructive in the learning process, thinking about their own thinking and using this knowledge to guide both thinking and behavior [11]. These expert learners are strategic and purposeful: establishing goals, planning, self-monitoring, self-evaluating, giving self-feedback and correction, and motivating themselves toward the desired end [31].

However, strategic learning is an internal monitoring system, and is implicit. To a less strategic learner, the "how" of learning is not obvious, and denies access to both process and content. Meta-cognitive learning strategies make the covert activities of expert learners overt, enabling struggling learners to engage in, practice, and eventually internalize ways to guide their own thinking, motivation, and behaviors to meet learning goals. Learning strategies are techniques, principles, or rules that enable a student to learn, solve problems, and to complete tasks independently [10]. The foundational idea of learning strategies is to support all learners in becoming independent by directly teaching them the processes that expert learners use.

Mnemonic devices are one such scaffold [40]. The mnemonic, TIPP&SEE, cues students to engage purposefully in a series of strategic steps and procedures that are foundational to higher order thinking skills [31], in this case, for computer science learning and problem solving.

2.2 Reading Comprehension

Learning to program is highly dependent on reading comprehension at several stages – reading (a) individual instructions, (b) a sequence of instructions provided as an example or starting code, (c) one's own partially-completed code, or (d) one's completed but incorrect code. To succeed, students must make meaning of the sequences of words into instructions (like sentences) and the sequences of instructions into functions or programs (like paragraphs).

We draw from two existing evidence-based reading comprehension strategies in designing TIPP&SEE: previewing and text structure.

Previewing enables students to set goals for reading and activates their prior knowledge [20, 25]. When reading example code for a new concept, students could scan the code to identify familiar and unfamiliar concepts. They could think about their prior knowledge of the concepts, predict how the new concept might work, and inspect the syntax of the new concept. The first half, *TIPP*, draws from previewing strategies.*TIPP*, which stands for Title, Instructions, Purpose, and Play, guides students in previewing different aspects of a new Scratch project before looking at any code. As a last step, they run the code with very deliberate observations of the events and actions that occur.

Text structure equips students to identify disciplinary-specific text structures, which guide comprehension [16, 46]. In CS, programming languages and environments have unique structures (e.g. loops, parallelism, sequence) that students must adopt to comprehend code and be able to discern as they learn new languages and environments. Text structure strategies inspired the second half, *SEE*, which stands for Sprites, Events, and Explore. *SEE* provides a roadmap for finding code in the Scratch interface (clicking on the sprite and finding the event) and proceduralizes the process by which they can learn how code works by deliberate tinkering.

3 RELATED WORKS

We build upon two bodies of work: CS education pedagogy and equity in CS learning opportunities. TIPP&SEE is a learning strategy that draws from CS pedagogy with the goal of providing learning opportunities that are effective for all students.

3.1 CS Education Pedagogy

Just as in other subjects, there is much debate on the best instructional approach for CS/CT: open-ended, exploratory experiences or direct instruction [5, 41]. Constructionism proposes that individuals learn best when they are expressing themselves through an artifact for public consumption, stressing self-directed learning [17]. This inspired Scratch, a popular programming language and development environment used in elementary schools [14], to foster a 'remix' culture, where people draw from others' projects.

Nonetheless, open-ended exploration may not lead to immediate comprehension of the concepts underlying their artifacts, especially when compared to a more explicit instructional approach [2, 23]. However, an excessively structured approach can discourage students from seeking additional CS instruction [44]. The Zone of Proximal Flow, a combination of Vygotsky's Zone of Proximal Development theory with Csikszentmihalyi's ideas about Flow [1, 42, 9], can help strike a balance between both approaches. The Zone of Proximal Flow refers to learning experiences that are not too challenging as to overwhelm students, but not too easy as to diminish learning opportunities.

Use−>Modify−>Create is one such moderate approach. It first provides more scaffolded, guided instruction for each concept, followed by a more open-ended project to engage students' interest and creativity [22]. However, there is limited prior work about how such approaches support students who face academic challenges, notably economic disadvantages, limited English proficiency (LEP), low reading and math proficiency, and/or disabilities.

3.2 Equity in CS Education

Inequities in CS education learning opportunities are well- documented in the literature. In her seminal works on gender [27] and race [26] in computing, Margolis identified structural and economic barriers, as well as shortcomings in curriculum and teacher professional development, as obstacles to the participation of diverse students in CS. Further, a national landscape study of the CS10K initiative, the predecessor of CS for All, pinpointed gaps in teacher professional development opportunities [15].

More recently, school districts and scholars have disseminated results of a nationwide CS for All implementation. A survey of households and schools revealed that although there was high demand for CS education from both parents and students, over 75% of principals reported their school did not offer computer science with programming or coding [43]. A study of New York City schools found that schools offering CS courses and activities served fewer Black and Latinx students and more white and Asian students [13].

Even if school districts widely offer CS opportunities, it is not guaranteed that such opportunities are effective for all students. School performance level, a proxy for race and socioeconomic status in the US [19, 32], has been linked to CS/CT learning outcomes of students [36]. A study of Florida schools found an association between faster progress through a Code.org curriculum and higher literacy scores [6]. Another study found that students demonstrating reading and math skills below grade level under-performed in an introductory CS/CT curriculum [37].

4 METHODS

In this section, we outline our curriculum, study design, assessment design, and data analysis.

4.1 Scratch Act 1

Within a semester (approximately six months), students completed Scratch Act 1 [39], an introductory computational thinking (CT) curriculum modified from the Creative Computing curriculum [8]. Scratch Act 1 consists of three modules, one for each of the key CT concepts (sequence, events, and loops). Each module used Use/Modify projects to introduce the CT concept, and culminated in a Create project (see Table 1). All curriculum materials were available in both English and Spanish and language selection in bilingual classrooms were up to teacher and student discretion.

Module	Project	Use-Modify-Create
Sequence	Name Poem	Use/Modify
	Ladybug Scramble	Use/Modify
	5 Block Challenge	Create
Events	Events Ofrenda	Use/Modify
	About Me	Create
Loops	Build a Band	Use/Modify
	Interactive Story	Create

Table 1: Scratch Act 1 Modules

4.2 Study Design

Fifteen teachers were recruited from a large, urban school district in Texas, USA, and underwent the same professional development to teach the Scratch Act 1 curriculum. Eight fourth grade teachers were taught the TIPP&SEE learning strategy. A total of 16 classrooms participated in the study, six of which were bilingual classrooms. Each classroom was assisted by an undergraduate CS researcher. Teachers were randomly assigned to either the TIPP&SEE or the comparison condition, resulting in five English-only and three bilingual classrooms in each condition. Classrooms in the comparison condition were taught Scratch Act 1 without the TIPP&SEE worksheets guiding them through the Use/Modify projects. After excluding students who switched schools or were chronically absent, there were a total of 96 and 88 students in the comparison and TIPP&SEE condition respectively.

Students were identified as economically disadvantaged if they received free/reduced lunch at school. Students who have limited English proficiency, a disability, or were below proficiency in reading and math proficiency were identified through state testing and district-provided demographic data. Some students fulfilled more than one of these characteristics. The distribution of students in each condition is shown in Table 2.

	TIPP&SEE	Comparison
Economically Disadvantaged	70	91
Special Education/Disability	16	15
Limited English Proficiency	25	52
Below Grade Level in Reading	54	46
Below Grade Level in Math	55	59

Table 2: Diverse Students in Each Condition

4.3 Assessment Design

Students took two pen-and-paper assessments, the first one after the Events & Sequence module and the second one after the Loops module. Each assessment consisted of a mix of multiple-choice, fill-in-the-blank and open response questions, and were designed to take 20-30 minutes to complete.

Following the Evidence-Centered Design framework [29], assessments were designed based on K-8 learning trajectories for elementary computing [33]. Questions were evaluated by a team of researchers and practitioners from CS and education, and tested with students from the previous school year for face validity.

Cronbach's alpha (α) was calculated for internal reliability between questions on the same topic. Between the questions and sub-questions on both assessments, 5 items targeted events (α=.72), 4 items targeted sequence (α=.7), and 9 items targeted loops (α=.85). A question with parallel loops was excluded in the reliability calculation because its inclusion lowered the the reliability of the loops questions (α=.82), suggesting that it was not testing the same concepts as the other questions. An understanding of the concept of parallelism, instead of loops, was likely more crucial to answering this question correctly.

For a more fine-grained picture, an exploratory factor analysis was conducted on student scores to characterize the underlying structure of our questions, i.e. which questions tested the same concept and the same level of Bloom's Taxonomy, a framework for classifying learning objectives [3]. Questions with multiple parts were treated as separate items. We excluded two questions from this analysis: a question on parallelism because of the Cronbach's alpha results, and an extra credit question on nested loops because that concept was not explicitly covered in the curriculum. A maximum likelihood factor analysis was conducted with six factors, the minimum number of factors that was deemed sufficient, and with the varimax rotation, which rotates the orthogonal basis so that the factors are not correlated. Based on the factor loadings from this analysis, we drafted a test blueprint (Table 3). We only included five of the six factors, as the last factor only accounted for one question. The remaining five factors accounted for 12 of the 18 questions included in the factor analysis.

	Remember	Understand
Scratch Basics	E&S Q2, Q3 (Loading=1.07)	—
Events	—	E&S Q4a, Q4b (Loading=1.90)
Sequence	—	E&S Q6, Q7b (Loading=2.08); L: Q5a,b,c (Loading=1.90)
Loops	—	L: Q1, Q2, Q4 (Loading=1.90); L: Q5a,b,c (Loading=1.90)

Table 3: Test Blueprint with Concept & Bloom's Level

4.4 Data Analysis

The assessments were scored by two researchers to ensure reliability. To see if TIPP&SEE and/or any of the student categories had an influence on their performance, we transformed our data using the Aligned Rank Transform (ART), which allows for non-parametric factorial analyses, prior to running an ANOVA F-test [18, 47]. A non-parametric transformation was selected due to small sample sizes in the academic challenge categories. Type III sum of squares was used to account for unequal sample sizes. Estimated marginal means were used for post-hoc comparisons between each group. For statistical significance, we report F and p values for both condition (TIPP&SEE vs Comparison) and academic challenge. We also report the eta squared (η^2) effect size. The effect size indicates the magnitude of the observed effect or relationship between variables [24]. η^2 measures the proportion of the total variance in a dependent variable (DV) that is associated with the membership of different groups defined by an independent variable (IV) [7]. For example, if an IV has a η^2 of 0.25, that means that 25% of a DV's variance is associated with that IV.

5 RESULTS

We first discuss high-level results, describing overall performance on the two end-of-module assessments of each student category. We then delve deeper into performance in specific concepts.

5.1 Overall Results

Finding 1: All student groups performed statistically-significantly better when using TIPP&SEE.

Across all five categories, students using TIPP&SEE performed better than students in the comparison group for both the Events & Sequence and Loops assessments (Table 4).

Finding 2: The gap between students with and without academic challenges was narrowed by TIPP&SEE.

Students facing any academic challenge, except for limited English proficiency, still statistically-significantly under-performed students without any challenges in both assessments (Table 5). However, the gap between students with and without any academic challenge was smaller in the TIPP&SEE condition compared with the comparison condition (Figures 1, 2, 3, 4, & 5).

Most notably, post-hoc comparisons revealed that there were no statistically-significant performance differences between comparison students *without* any academic challenges and TIPP&SEE students *with* economic disadvantages ($p = .66$), disabilities (E&S: $p = .12$; Loops: $p = .69$), and proficiencies below grade level in math (E&S: $p = .63$; Loops: $p = .37$) and reading (E&S: $p = .55$; Loops: $p = .14$). This suggests that TIPP&SEE scaffold CS/CT learning for diverse learners such that they achieve similarly to their peers who do not face academic challenges.

Finding 3: Limited English proficiency was the only student characteristic not associated with assessment performance.

The only exception to these trends was limited English proficiency, which did not have a statistically-significant association in either assessment (E&S: $p = .52$, Loops: $p = .19$). This may be due to bilingual instruction in both conditions. Not only were LEP students taught in Spanish and English, they also had access to Spanish CS materials and could even translate Scratch into Spanish.

	E & S		Loops	
	$F(1,181)$	η_p^2	$F(1,178)$	η_p^2
Economic Disadvantage	8.06**	.043	11.92**	.063
Disability Status	21.25**	.11	19.53**	.098
Limited English Proficiency	18.93**	.095	17.23**	.088
Below Grade Level in Reading	21.64**	.11	32.92**	.16
Below Grade Level in Math	9.95**	.052	36.52**	.17

$^*p < .05; ^{**}p < .01$

Table 4: Significance Values for *Condition (TIPP&SEE vs Comparison)* in each Student Category

	E & S		Loops	
	$F(1,181)$	η_p^2	$F(1,178)$	η_p^2
Economic Disadvantage	10.76**	.056	8.72**	.047
Disability Status	25.26**	.12	27.96**	.14
Limited English Proficiency	–	–	–	–
Below Grade Level in Reading	54.48**	.23	64.31**	.27
Below Grade Level in Math	34.05**	.16	53.92**	.23

$^*p < .05; ^{**}p < .01$

Table 5: Significance Values for each *Student Characteristic (Disability, LEP, etc)*

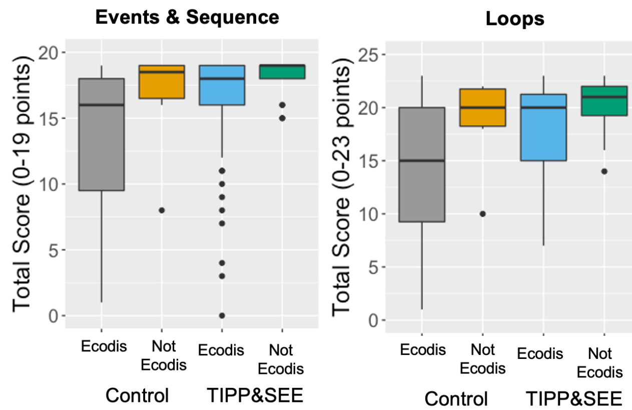

Figure 1: Scores of Economically Disadvantaged Students (ECODIS)

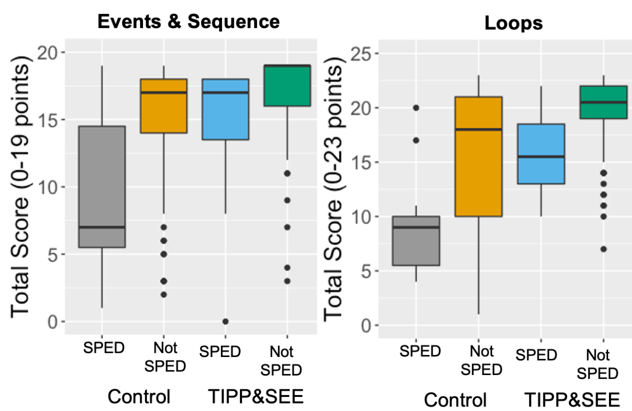

Figure 2: Scores of Students with Disabilities (SPED)

5.2 Concept-Specific Results

We now turn our attention to the specific concepts covered in the end-of-module assessments, organizing questions based on the results of an exploratory factor analysis.

Finding 4: There were statistically-significant interactions between condition and disability status.

At the concept level, the interaction terms between condition (TIPP&SEE vs Comparison) and special education/disability status were statistically significant for most questions, which limits our interpretation of the data. As such, we do not further discuss them

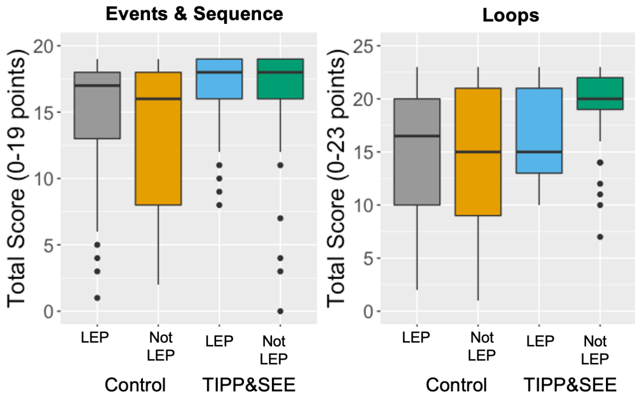

Figure 3: Scores of Limited English Proficiency Students (LEP)

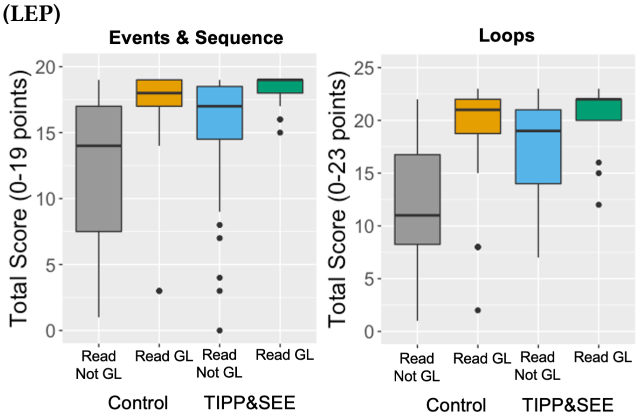

Figure 4: Scores of Students Reading Below Grade Level

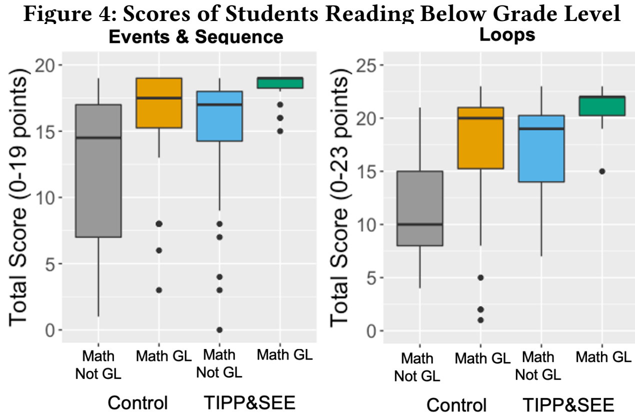

Figure 5: Scores of Students with Math Below Grade Level

in this section. Potential reasons for these interactions are explored in the next section, §6. In this section, we delve deeper into the other student categories: students with economic disadvantages, students with limited English proficiency, and students performing below grade level in reading and math.

5.2.1 Events. For the two questions on Events (Q4a and Q4b from the Events & Sequence assessment; Table 3), students were shown a Scratch stage with two sprites that resulted from a green flag click and asked to identify the script that ran for each sprite.

Finding 5: LEP status was not associated with Events performance, while economic disadvantage and math proficiency had mixed results. Reading proficiency was associated, regardless of condition.

Just as in the overall results, for students with limited English proficiency, neither LEP status (Q4a: $p = .56$, Q4b: $p = .89$) nor condition (Q4a: $p = .78$, Q4b: $p = .91$) were statistically significant. In contrast, results for students with economic disadvantages and students performing below grade level in math were mixed, where one question would have neither student category nor condition as statistically-significant but the other question would have one of them significant.

Interestingly, students who were below grade level in reading struggled on these questions, regardless of condition (Q4a: $p < .01; \eta_p^2 = .075$; Q4b: $p < .01; \eta_p^2 = .069$). This finding may be further evidence of a trend shown in prior work where a text surface understanding of code was tied to reading comprehension [37].

5.2.2 Sequence. In two of the questions on Sequence (Q6 and Q7b from the Events & Sequence assessment), students were shown a script and asked to articulate the order in which the different blocks would run. The remaining three Sequence questions (Q5a, b, c from the Loops assessment) asked about the same script, where a loop was sandwiched between two blocks. Students were asked to identify the blocks that ran before, after, and in the loop.

Finding 6: Sequence results were mixed for students with economic disadvantages, disabilities, and below grade level proficiency in reading and math.

For the remaining student categories, results were mixed, with some of the questions having the condition significant, the student category significant, both significant, or none significant (Table 6).

5.2.3 Loops. Q5a, b, and c from the Loops assessment also covered Loops in addition to Sequence. One of the Loops question (Q1 from the Loops assessment) showed students a loop and asked students how many times the loop would repeat. Two other Loops questions (Q2 and Q4 from the Loops assessment) asked students to unroll a loop, but with different answer choices. Q2 asked about a single-block loop repeating 4 times and had the answer choices of the block in the loop repeated 1, 2, 3, or 4 times. Q4 asked about a double-block loop repeating 3 times and had the answer choices of the two blocks alternating 3 times (the correct execution) and a script with the first block repeated 3 times followed by the second block repeated 3 times (a common misconception).

Finding 7: Loops results were mixed for students with economic disadvantages, disabilities, and below grade level proficiency in reading and math.

Just like in Sequence, results were similarly mixed for the rest of the student categories, with different combinations of condition and student category found to be statistically significant for different questions (Table 6).

6 DISCUSSION & IMPLICATIONS

We now return to our overarching research questions:

- To what extent does the meta-cognitive strategy TIPP&SEE support diverse learners in CS/CT instruction?
- In which CS/CT concepts are diverse learners supported by TIPP&SEE?

		Condition		Category	
		F	η_p^2	F	η_p^2
Economic Disadvantage					
Sequence	E&S: Q6	8.58**	.045	8.38**	.044
	E&S: Q7b	13.99**	.072	18.59**	.093
Sequence & Loops	L: Q5a	—	—	—	—
	L: Q5b	17.43**	.089	4.56*	.025
	L: Q5c	—	—	5.07*	.0028
Loops	L: Q1	5.98*	.033	—	—
	L: Q2	—	—	5.48*	.029
	L: Q4	—	—	8.45**	.0045
Limited English Proficiency					
Sequence	E&S: Q6	18.22**	.091	5.01*	.027
	E&S: Q7b	15.31**	.078	10.59**	.055
Sequence & Loops	L: Q5a	—	—	—	—
	L: Q5b	—	—	4.09*	.022
	L: Q5c	53.17**	.23	—	—
Loops	L: Q1	25.19**	.12	13.25**	.069
	L: Q2	26.64**	.13	5.46*	.029
	L: Q4	29.65**	.14	17.55**	.089
Below Grade Level in Reading					
Sequence	E&S: Q6	7.11**	.038	20.71**	.10
	E&S: Q7b	8.65**	.046	29.86**	.14
Sequence & Loops	L: Q5a	12.01**	.064	36.44**	.17
	L: Q5b	8.99**	.049	21.67**	.11
	L: Q5c	8.60**	.047	19.87**	.10
Loops	L: Q1	7.05**	.039	—	—
	L: Q2	42.25**	.19	24.69**	.12
	L: Q4	24.10**	.12	8.79**	.048
Below Grade Level in Math					
Sequence	E&S: Q6	8.56**	.045	11.83**	.062
	E&S: Q7b	16.94**	.086	22.95**	.11
Sequence & Loops	L: Q5a	20.50**	.10	31.53**	.15
	L: Q5b	—	—	30.13**	.15
	L: Q5c	—	—	30.13**	.15
Loops	L: Q1	5.25*	.028	—	—
	L: Q2	50.8**	.22	22.01**	.11
	L: Q4	39.29**	.18	31.75**	.15

$^{*}p < .05;^{**}p < .01$

Table 6: Significance Values for Sequence & Loops Questions

For our first research question, our findings provide preliminary evidence that support the use of meta-cognitive strategy instruction in CS/CT for diverse learners who typically under-perform on critical academic outcomes, such as the state level assessments employed in this analysis, and on national assessments of math and reading [30]. In this study, CS instruction using the TIPP&SEE strategy to scaffold the Use–>Modify–>Create framework within a Scratch curriculum for fourth grade students effectively leveled the playing field. This squares with findings from math and science education, where open inquiry was less effective than scaffolded inquiry for students with disabilities [21, 28, 34]. TIPP&SEE enabled students in poverty, students with disabilities, and students who were performing below proficiency on state testing in reading and math to perform similarly to their typically achieving peers on CS tasks.

The only exception to this trend were multi-lingual learners. The performance of multi-lingual learners in bilingual classrooms was not enhanced by exposure to the learning strategy and their performance across instructional conditions was similar. In comparison to their typically developing peers, they slightly under-performed on the Loops assessment ($p < .05$), but did not perform differently on the Events & Sequence assessment ($p = .31$). Although prior studies have shown open inquiry to be less effective for multi-lingual learners [4, 12, 45], limited English proficiency was less of a barrier to their CS/CT instruction with bilingual instruction [35].

For our second research question, results were less definitive. There were statistically-significant interactions between condition and special education/disability status for a majority of the questions. While we balanced the number of students with disabilities in each condition as best as possible (see Table 2), a student classified as having a disability could have one of many different kinds of disabilities, ranging from visual impairment to dyslexia. We only had data on *if* they had a disability, but not *what type of* disability. It is possible that TIPP&SEE supported students with certain kinds of disabilities better than others, which would require further investigation.

On the Events questions, students with limited English proficiency exhibited the same trend as the overall assessment results, while results were mixed for students with economic disadvantages and with below grade level proficiency in math. TIPP&SEE did not do much to support students who were reading below grade level on these questions, suggesting that reading may be a foundational skill to programming.

On questions covering both Sequence and Loops, results were inconclusive for all student categories. There are several potential reasons for this. We may need to look at more specific cognitive factors, such as working memory; these student categories may be obscuring these cognitive factors. We may also need to revise our questions as they may be too high-level or include too many steps, and design more questions that target different levels of the Bloom's taxonomy as our current test blueprint mainly targets understanding. It may also be a reason we have not yet considered; future exploration will be necessary for more conclusive results. While the gap between students with and without an academic challenge narrowed with TIPP&SEE in aggregate, further research is required to identify which concepts are and are not served by the TIPP&SEE strategy, and for which student demographics.

While this is exploratory research and a single study, the promise for fulfilling the goal of CS for All to support diverse learners is encouraging. We hope that learning strategies like TIPP&SEE will help foster meaningful participation in computing through the intentional focus on improving equity and access to CS/CT for all.

7 LIMITATIONS

This study was only done in one school district using state-defined metrics for each student category. Additionally, we did not control for teacher and classroom effects, such as the implementation of bilingual instruction, due to resource limitations and small sample size. More research is needed to replicate and extend this work.

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