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Collaborative Math Learning Facilitated by an Intelligent Agent

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Abstract: Collaborative learning, a proven method for supporting differentiated learning, is often underutilized in schools, particularly when there are staffing challenges to facilitate and monitor group interactions. OKO is an intelligent platform for small-group collaborative learning in elementary and middle school classrooms, with an initial focus on math games and puzzles. It leverages an Artificial Intelligence-based agent to interact with small groups of students, facilitating social and collaborative activities. This paper introduces the OKO collaborative learning platform and examines how using OKO in small groups over a two-week period in classrooms affected student math learning, attitudes towards math, and collaboration skills. Despite a short implementation period, findings suggest that OKO shows promise in improving math learning and reducing math anxiety. The paper also discusses how teacher training can better support implementation of the program in classrooms.

Introduction

Elementary education is grappling with the dual challenge of closing math achievement gaps and nurturing social-emotional skills. The latest National Assessment of Educational Progress (NAEP) data underscores this, with just 36% of fourth graders demonstrating math proficiency (NCES, 2022). Simultaneously, the development of social-emotional competencies, essential for overall academic success and well-being, is increasingly prioritized (Jones et al., 2021).

Collaborative learning is an approach to learning and teaching that involves groups of learners working together to solve problems or complete tasks (Laal & Ghodsi, 2012). The group has a common goal and shares responsibility for each other's learning such that the success of one can help others also be successful. Research has demonstrated the multifaceted benefits of collaborative learning. Students learn better during collaboration when they engage in an active cognitive process (Prince, 2004), which contributes to greater engagement and motivation in their work (Anderson, 2003). Collaborative learning has a positive effect on critical thinking abilities (Lee et al., 2014; Sulisworo & Syarif, 2018), contributing to cognitive learning (Chee et al., 2018) and social-emotional learning (Tolmie et al., 2010). In addition, research has found that students learn math effectively when they engage in mathematical discourse—when they compare, share, explain or justify solution methods (Bell & Pape, 2012; Cirillo, 2013).

On the other hand, collaborative learning requires intentional facilitation to be truly effective, as it depends on skilled guidance to ensure that a group of students actively engage with one another, stay focused on learning objectives, develop clear communication and teamwork skills, and contribute meaningfully. Without proper facilitation and active management of group dynamics, collaborative efforts may lack direction, leading to disengagement or unproductive interactions among students (Le et al., 2017). Thus, despite extensive research highlighting the significant effects of collaborative learning in enhancing student engagement, critical thinking, and academic achievement, it remains underutilized in classrooms, particularly in small group settings—a proven method for differentiated instruction. This gap is especially pronounced in underserved communities, where systematic challenges, including teacher staffing shortages and limited access to professional development, hinder the enablement of effective small group collaborative learning.

OKO, a multimodal intelligent assistant for small group collaborative learning

OKO is an intelligent platform for small-group collaborative learning in elementary and middle school classrooms, with an initial focus on math games and puzzles. OKO leverages multimodal artificial intelligence (AI), combining computer vision for gesture, pose, and attention recognition, as well as voice recognition, voice synthesis, and conversational interface design, to interact naturally with small groups of students, facilitating social and collaborative activities.

How OKO Works

OKO consists of a web-based client application with separate experiences for students and teachers. The student and teacher experiences are entirely web-based, and they work on any device with a browser and camera with headset, such as Chromebooks or laptops. OKO's backend services processes live streaming video, extracting facial, hand, and skeletal key points, and it recognizes the gestures and poses in real time. OKO transcribes student live speeches and automatically generates responding speech for the facilitating agent. At the nexus of the multimodal inputs of student activity is OKO's Orchestrator, which handles the main lesson workflow.

OKO uses a hybrid approach to facilitate small group work, combining the power of large language models (LLMs) with other AI techniques. OKO leverages LLMs to interpret student responses and discussions in real time, analyzing the content of their conversations. This LLM analysis is combined with data from computer vision-based gesture recognition and structured inputs from student responses (e.g., answers to multiple-choice questions) to provide a comprehensive picture of group dynamics and individual learning progress. This information then informs OKO's facilitation moves, which are powered by an expert system that leverages research-backed collaboration mechanics and effective facilitation strategies. This hybrid approach enables OKO to provide personalized support, promote equitable participation, and foster rich mathematical discourse within small groups.

Experience with OKO in the classrooms

OKO is designed primarily for use in elementary and middle school classrooms as a Multi-Tiered System of Supports (MTSS) Tier 1 and 2 interventions[1] during the school day, aiding teachers in differentiating their instruction through small group rotations. Rotations typically occupy a 60-minute block in 15–20-minute segments. OKO can be used in one or more stations, keeping learners engaged in cognitively demanding and curriculum-aligned work, while also enabling educators to focus their personal attention as appropriate and reduce their need to monitor each station. Using multimodal AI technology, OKO functions as an in-class teaching assistant while students are using the platform, extending what teachers have been teaching in classrooms by supporting students with prompts to learn from one another.

To use OKO in the classroom, students connect to an OKO session on independent devices and work together collaboratively. Figure 1 shows a typical set up in a classroom using OKO with a group of four students. An AI-driven, speech-enabled facilitating agent promotes group interaction and collaboration based on the answers students provide and their participation in the group discussion, ensuring each student actively participates and contributes to group problem-solving. Having a facilitating agent that actively promotes student engagement in small group discussion then overcomes the limitations of traditional digital learning methodologies that often promote passive consumption or individual competition. Since OKO can marshal a wide range of curriculum-aligned tasks, teachers essentially have an in-class assistant who can extend precisely what they have been teaching. For teachers, that is extremely attractive: it allows them to efficiently differentiate instruction and target groups of students and their particular needs without being present with each group all the time. Because OKO works on any device with a webcam and headset, it can also be flexibly used for hybrid and remote learning environments. The teacher experience provides simple group setup and administration tools, and reporting functionality for educators to examine the results of the sessions their students have completed with OKO and to plan their next activities accordingly.

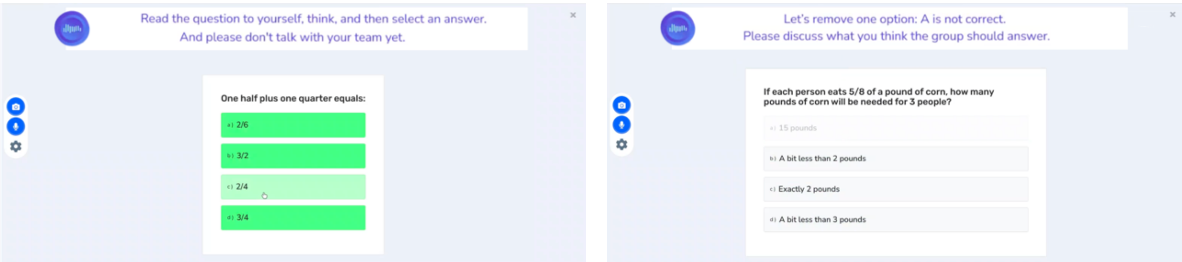
Figure 1
Students Playing Let's Talk in Class

Let's Talk game

Let's Talk is OKO's new consensus-building game, drawing from existing standards-aligned math problems with content planned to cover grades K-8. The study was focused on fraction problems for 4th and 5th grade students. In Let's Talk, OKO challenges students to independently solve a math problem and then prompts the group to discuss and agree on an answer together.

Let's Talk starts with a brief, engaging introduction to the game. The group is presented with a multiple-choice fractions problem, and each student independently selects an answer (see Figure 2a). OKO tracks each student's response but does not provide feedback at this stage. After all students have submitted their solutions, OKO uses a voice command to inform the group whether they agree or not. If there is no consensus, students are told which answers were selected by the group, and then they are encouraged to discuss the problem and try again (see Figure 2b). If the group still doesn't agree on the correct answer, OKO helps the group by removing one of the wrong options. The round ends either with OKO congratulating the group on arriving at the correct answer or a brief consolation ("That was a tricky question"). The game then proceeds to the next challenge. Let's Talk encourages communication and discourse, the sharing of knowledge, and development of social-emotional learning competencies. This game was inspired by the Consensus game conceived by Miguel Nussbaum and studied by Roschelle and colleagues in TechPALS (Roschelle et al., 2010), and extends OKO firmly into the field of computer-supported collaborative learning (CSCL), inspiring social-emotional learning through a scaffolded collaborative activity.

Figure 2
OKO Let's Talk Interface: Initial Round (a) and Round 2 (b)



(a) (b)

We conducted a study to examine whether Let's Talk, with a focus on 4th and 5th grade fraction content may promote student learning. The research questions (RQs) that guided this study were:

1. Do students show increased proficiency with fractions, more positive attitudes, and less anxiety towards math after using OKO?
2. Does OKO effectively prompt students to engage in discussion and collaborative problem solving?
3. Do the training and teacher preparation materials sufficiently prepare teachers to use Let's Talk to facilitate small group problem solving sessions?

Related research

OKO is grounded in research from a variety of fields, including computer science, learning science, and psychology. In particular, there is a wealth of research that supports the effectiveness of collaborative learning and discourse, the benefits of social-emotional learning, and the importance of using technology to support differentiated instruction. Research on collaborative learning has shown that it has positive effects on student math achievement (Alam et al., 2021; Ahmad & Dogar, 2023; Chiuphae, 2023; OECD, 2016; Schreiber & Valle, 2013; Siller & Ahmed, 2024). The OKO platform encourages students to actively engage with one another while playing games. By engaging in relevant cognitive processes, students are able to learn better, which can impact academic success (Mayer et al., 2009).

OKO is also designed to promote social-emotional learning, which can be highly effective in promoting student success in school and beyond (Durlak et al., 2011; Tolmie et al., 2010). In particular, collaborative learning supports student attitudes towards math in terms of their self-confidence, perceived value and enjoyment of math, and motivation (OECD, 2016; Schreiber & Valle, 2013; Siller & Ahmed, 2024). A longitudinal study in elementary school classrooms found that students' positive attitudes towards math due to a collaborative learning intervention lasted after the study had ended (Huang et al., 2012). Collaborative learning also reduces student anxiety toward math, as students learn in a supportive and less intimidating environment (Chen et al., 2018; Muis et al., 2018). As students actively engage in their interactions with one another, they begin to better understand their differences and work on resolving problems that could arise (Johnson & Johnson, 1985), and this could foster engagement and enjoyment in mathematics (Johnson & Johnson, 2014).

Roschelle et al. (2010) found that technology-enhanced collaborative problem-solving tools can be highly effective in promoting student collaboration and communication. The project also highlighted the importance of providing scaffolding and guidance to students in order to promote effective collaboration and problem-solving. The principles and approaches used in the TechPALS project align closely with the approach used in the development of OKO.

Methods

Participants and procedure

We conducted a study with six 4th and four 5th grade teachers and their 299 students. The teachers and students were from 11 classrooms in the USA that spanned across three charter schools in Georgia and one public school in Tennessee. Student demographic data was not collected as a part of the study. Teachers used Let's Talk in their classrooms for 20-minute sessions twice a week over two to three weeks of implementation. Teachers decided how to group students and when during the school day they wanted to use OKO with students. Prior to implementation, teachers administered a pre-survey and pre-assessments with students. All assessments and surveys were taken online. A sample of six classrooms were observed, and six teachers were interviewed. At the end of the implementation, teachers administered a post-survey and post-assessments to students. A teacher report of student usage data that included information on how much time students/groups spent in the game, as well as when students logged in and out of the game was sent to teachers at the end of the usage period.

Measures

Data for the study consisted of student pre- and post-assessments and surveys, classroom observations, and teacher end-of-study interviews. The individual measures are described in detail below.

Student math content assessment

Students completed a proximal assessment of their knowledge and skills of fractions before and after using Let's Talk. Researchers constructed the assessment by selecting 11 questions from the Fourth Grade Fractions Battery (Fuchs et al., 2023), a validated battery assessing the fractions performance of 4th grade students. The selected questions were aligned with the fractions content that students would encounter during the two-week usage period. Using the Kuder-Richardson Formula 20 (KR-20) test for reliability, the constructed assessment had a score of 0.85 based on students' pre-assessment responses, suggesting good reliability.

Student math attitudinal survey

Students completed pre- and post-attitudinal surveys that included two subscales from the PISA student survey (OECD, 2014). These subscales were *Interest in Mathematics and Mathematics Anxiety*. The response categories for these questions used a five-point Likert scale ("Strongly agree," "Agree," "Neither Agree nor Disagree," "Disagree," and "Strongly disagree").

- The *Interest in Mathematics* subscale had four items on whether students enjoyed mathematics, e.g. "I do math because I enjoy it," "I enjoy reading about math," and "I look forward to my math lessons." This subscale had good internal consistency (Cronbach's a = 0.80), compared to what has been reported in data from the United States (a = 0.91) (OECD, 2014).
- The *Mathematics Anxiety* subscale had five items relating to how nervous, tense, or helpless students felt when working on math problems, and whether they were worried about getting poor grades in mathematics. These items were reverse coded such that higher scores on the scale indicated that students were less anxious. This subscale also had good internal consistency (a = 0.83), compared to what has been reported in data from the United States (a = 0.88) (OECD, 2014).

The student post-survey included six researcher-developed questions related to student experiences playing Let's Talk and frequency of group work.

Classroom observations

A sample of six classroom periods from a mix of schools in Georgia and Tennessee were observed for approximately 45-60 minutes per session. During each observation, the researcher collected a running record of student engagement, teacher facilitation (if any), and any indication of student learning or collaboration. After each session, the researcher reflected on the overall classroom feasibility, and student engagement and learning.

Teacher post-interview

Post-study interviews were conducted via Zoom virtual meetings with 6 teachers to gather formative feedback on the game experience in order to inform actionable feedback for OKO about future product revisions. The interviews followed a semi-structured protocol and lasted 30-40 minutes, during which the teachers were asked to reflect on implementation, student engagement and learning, helpfulness of the training and teacher preparation materials, and areas of improvement for the product.

Data analysis procedures

Pre- and post- assessments and surveys were cleaned and coded for accuracy. The final analytic sample had 268 students who completed both pre- and post-assessments (89.6%) and 254 students who completed pre- and post-surveys (84.9%). The assessment scores and survey responses were then analyzed using hierarchical paired sample t-tests to see if students' scores increased from pre- to post-assessment or surveys, and whether the differences between pre- and post-scores were significantly different from zero. The hierarchical test accounts for the nesting of students within teachers. Classroom observations and teacher interviews were qualitatively coded and analyzed. Major themes and patterns were identified to help address the study research questions.

Results

RQ1: Did students show increased proficiency with fractions and more positive attitudes and less anxiety towards math after using OKO?

Increased student skill in fractions

Across all students who had matched pre- and post-assessment data (n = 268), there was an average 7% increase in students' overall score from pre- to post-assessment. The average score for the post-assessment (mean [M] = 10.85, standard deviation [SD] = 4.22) was significantly higher than the pre-assessment (M = 11.98, SD = 4.01), t(10.24) = 3.45, p =.006. Scores were out of a total score of 17.

An analysis by grade levels indicated that the gains in student assessment scores were significant for students in 4^{th} grade (n = 139), but not for students in 5^{th} grade (n = 129). Students in 4^{th} grade had significantly higher average post-assessment scores (M = 10.87, SD = 4.12) compared to pre-assessment (M = 8.94, SD = 3.80), $t(138) = 6.04$, $p < .001$, which represents an 11% gain in test scores. However, students in 5^{th} grade exhibited only a 2% gain in their post-assessment scores (M = 13.17, SD = 3.52) compared to pre-assessment (M = 12.91, SD = 3.64), $t(3.14) = 0.62$, $p = .557$. This suggests that Let's Talk may have been more helpful to 4^{th} grade students who were newer to fractions, compared to 5^{th} grade students who may have more experience with fractions.

Change in student anxiety toward math

Across students with matched pre- and post-survey results (n = 254), on average, there was a 2% improvement on students' feelings of anxiety towards math, and the difference was statistically significant at $p = 0.019$, indicating students were less anxious towards math at the end of the study period. There were no significant changes between pre- and post-survey results for students' interest in mathematics.

Added value to classroom lessons

Overall, teacher interviews indicate a positive perception of Let's Talk's value in the classroom. Teachers generally felt that Let's Talk helped students' math learning, although some teachers caveated that Let's Talk would further add value after resolving technical glitches and expanding its coverage of curriculum content. Teachers noted benefits, such as reinforcing prior mathematic skills, providing collaborative opportunities, and (for some teachers) facilitating differentiated learning. For instance, one teacher remarked:

> "Let's Talk was reinforcing [the math] skills that I've taught; it was also just also a reintroduction to the skills I may have taught...it [also adds value in that it] gives me the option to work with other students or to look over similar assignments they might have done and go back in and help students clear up misconceptions they might have. It frees the teachers up to do other things and to work with students on another level."

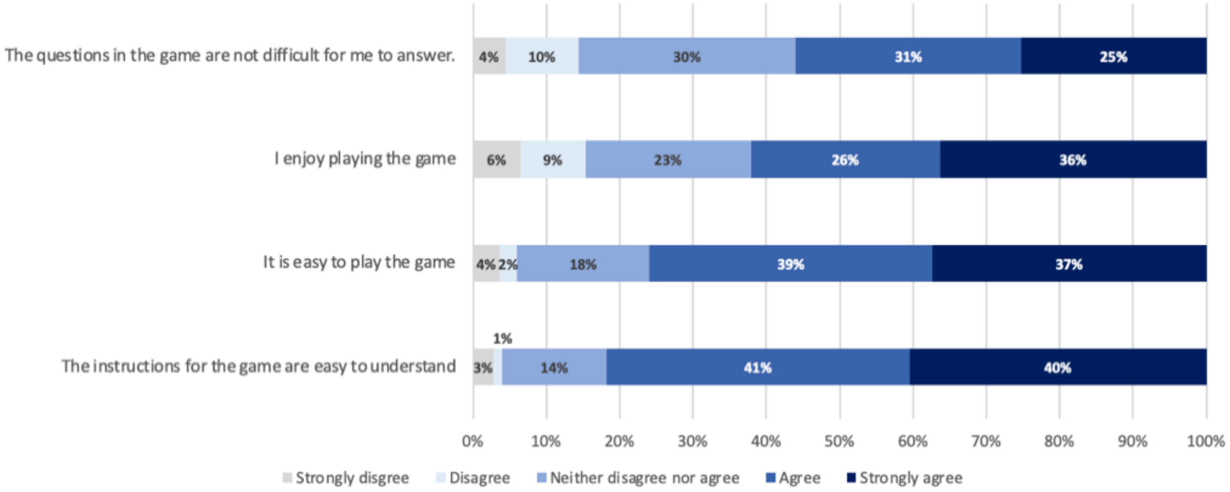
RQ2: During classroom use, does OKO effectively prompt students to engage in discussion and collaborative problem solving?

Positive student responses and rich mathematical discussion

In the post-survey, students were asked to rate different aspects of the game, student enjoyment, ease of use, and whether the content was grade appropriate. In Figure 3 below, we see that most of the students "Agreed" or "Strongly agreed" that they enjoyed playing the game, the content was easy to understand, and that it was easy to play the game.

In line with findings from the post-survey that students enjoyed playing Let's Talk, classroom observations also indicated that students showed strong engagement with the Let's Talk game. In the majority of observed gameplay sessions, students playing Let's Talk engaged in conversations about the math lesson content and asked related questions frequently or very frequently. The observer noted that some groups of students shared their answers with their classmates but didn't share their thought processes with each other. However, students in other groups effectively engaged in discussion, providing explanations of their thinking to their classmates with phrases like "I think it's 'A' because," "I don't think your answer is right because," and "I respectfully disagree with your answer." The observer noted a variety of student approaches to collaborative discussion, including students using a round robin approach.

Figure 3
Student Attitudes Towards Let's Talk (n = 254)



Researchers observed several instances where students in groups engaged in dynamic discussions and collaborative problem-solving processes. For example, in one group, a student asked their classmate how they got to their initial answer. After the student explained, the group decided that it was incorrect, and they all switched to another response. The answer they collectively decided upon was correct and the students celebrated. In another class, four out of five students in a group agreed upon an answer. One student used the example of splitting a chocolate bar into pieces to explain the solution to the remaining student, which helped the student understand and select the correct answer. In one group, students demonstrated an ability to successfully respond to the scenario, in which their initial response was incorrect, by discussing other possible solutions as a group. During a classroom observation, a student told the researcher, "We feel like we were learning from each other."

Post-study teacher interviews also substantiated observation findings. Most teachers found Let's Talk to effectively promote student engagement in discussion and collaborative problem-solving. Teachers shared that they observed instances where students actively worked through problems together, listened to peers' ideas, and engaged in clarifying discussions. Teachers noted instances where students with misconceptions had to explain their reasoning until it clicked for their peers, showcasing active engagement and peer learning. For example, one teacher shared:

> "[In] my higher group there were a couple of questions they were stuck on. They're all very strong personalities. The person who was correct really had to explain and explain and explain, and finally it clicked for the other two group members. It was neat to see that they were really stuck in their ways, so he was getting frustrated, and I encouraged correct student to keep explaining it..."

Another teacher reflected on the following example:

> "We were seeing and hearing academic language, we saw teamwork happening, I saw high fives. I heard, 'Yeah, we got it!' I've seen the excitement that comes from getting the answer

> correct and collaborating with each other, and hearing the discussion. I hear students say, 'This is wrong, because...' and literally explaining why they thought that answer was wrong and seeing someone counteract that response and defending that answer."

<u>Challenges and variation during classroom implementation</u>

While Let's Talk prompted students to engage in collaborative math discussions in most participating classrooms, teachers and students also experienced notable challenges with the game. One class included many students with Individualized Educational Plan (IEPs) who receive specialized instruction, supports, and services developed to meet the individual needs and students whose math proficiency was significantly below grade level. The class teacher shared that the fractions-focused content available in Let's Talk during the study exceeded the abilities of some students, leading to frustration and decreased engagement while using Let's Talk. They needed to provide substantial support to these students during gameplay, including frequent encouragement to continue with gameplay and assistance with tasks.

Classroom observations also revealed challenges when all students played simultaneously in small groups. Although this arrangement deviated from the intended implementation structure of small group rotation, some teachers attempted it, resulting in excessive noise and chaos.

According to OKO's backend usage data, there was variability in the implementation of Let's Talk in the classroom. Across the two-week implementation period, the number of days teachers used Let's Talk in their classrooms ranged between 2 to 8 days. The average number usage days was 5.3 ($SD = 1.9$), with an average number of 13.9 minutes per session ($SD = 2.3$). The variability and, in some classrooms, lower student usage data could be potentially explained by the technical obstacles that teachers and students encountered in the classroom.

These examples showcase the engagement and rich mathematical discussions that occurred while students used Let's Talk, demonstrating OKO's ability to prompt students to engage in collaborative problem solving. However, the study also highlighted the need to provide differentiated math learning content to support students at a wide range of achievement levels, and some students may need extra support to be able to effectively engage in the learning activities. Effective classroom management strategies and structures are essential to successfully integrate the game in classrooms.

RQ3: Did the training and teacher preparation materials sufficiently prepare teachers to use Let's Talk to facilitate small group problem solving sessions?

Before the start of the implementation, there was a 1-hour online teacher training that introduced teachers to Let's Talk and walked them through the teacher sign-up and student session set-up process. In addition, the developer also had a technology check with teachers before the start of the implementation, and they hosted office hours prior to the start of the study. During office hours, teachers could ask questions about logistics and gameplay.

When asked during the interviews, teachers revealed that they generally felt that the training and preparation materials were sufficient for implementation, primarily because they felt that implementing Let's Talk overall did not require extensive individual preparation nor a large teacher role while implementing. For example, one teacher noted: "Yeah, [the training] did [prepare me adequately]. I'm an inquisitive person. It left me with no clarifying questions, which is good. The emails with the scripts were easy to follow as well." Most teachers noted that implementing Let's Talk required minimal lesson preparation on their part. When asked, teachers shared that their lesson preparation mainly revolved around explaining expectations to students, ensuring students had necessary materials (such as headphones), and introducing the activity with a scripted explanation. Because their own individual preparation was not too involved and teachers mostly envisioned their role as a facilitator when implementing Let's Talk, teachers generally felt that the training materials were sufficient.

Conclusion

This paper introduces OKO, an intelligent platform for small-group collaborative learning that leverages multimodal AI to interact naturally with small groups of students, facilitating social and collaborative activities. It provides a flexible and effective means of supporting small group learning and promoting student success. It helps to make teachers' instruction more efficient, engaging, and effective, while also providing valuable opportunities for collaboration, communication, and critical thinking.

In a school-based study, we examined whether OKO shows promise in increasing students' math proficiency on fractions and social-emotional competencies using math. The results suggest that Let's Talk can be an engaging tool for math lessons and that students' skills in fractions increased during the period of time when Let's Talk was used. Teachers also noted that Let's Talk added value to classroom lessons in that it encouraged rich mathematical discussion and prompted collaboration opportunities. In addition, there were significant differences in levels of students' pre- and post-anxiety toward math. These were promising findings, given the short implementation period, and are in line with the current research on how collaborative learning can support student math achievement (Alam et al., 2021; Ahmad & Dogar, 2023; Chiuphae, 2023; OECD, 2016; Schreiber & Valle, 2013; Siller & Ahmed, 2024). However, results should also be interpreted with caution, as the sample was small and there was no comparison group. This makes it difficult to determine whether changes in student math achievement were directly the result of playing the game or were from external factors, such as students improving their math skills through classroom instruction and practicing. Further studies with experimental design are needed to establish rigorous evidence of Let's Talk's promise on improving student learning.

This study also contributes to research on challenges faced when implementing a collaboration-based technology program in the classroom. For example, training could have incorporated ways of troubleshooting technical issues that arose. Collaborative learning tasks should be vetted to match students' performance level. Overall, OKO is a valuable tool that supports differentiated instruction, promotes social-emotional well-being, and helps educators meet the diverse needs of their students in the K-12 classroom.

Post-study Update and Future Development Work

Since the study's completion, OKO has undergone significant development to enhance its capabilities and address the needs of educators and students. The platform now incorporates content aligned with the full K-8 Common Core State Standards for Math. Additionally, OKO now features a robust Educator Dashboard, which includes AI-generated summaries of session activity and tools to assist teachers with small group instructional planning.

OKO's ongoing development focuses on several key enhancements that include 1) expanded collaboration mechanics that incorporate additional collaboration mechanics to further enhance the platform's capacity for dynamic student collaboration, 2) adaptive facilitation capabilities to elicit richer mathematical discourse among students, and 3) gamification elements to further enhance student motivation and engagement. These enhancements, combined with a commitment for research and iterative development, will further strengthen OKO's ability to transform math instruction, promote equitable learning opportunities, and empower all students.

Endnotes

(1) In the US, Tier 1 interventions provide universal instruction for all students and Tier 2 interventions offer targeted support for students struggling with specific skills.

References

Ahmad, M., & Dogar, A. H. (2023). Effect of collaborative learning on conceptual understanding ability in mathematics among 5th grade neglected children. *Annals of Human and Social Sciences, 4*(2), 205-213. https://doi.org/10.35484/ahss.2023(4-II)19

Alam, M. J., Haque, A. K. M. M., & Banu, A. (2021). Academic supervision for improving quality education in primary schools of Bangladesh: Concept, issues and implications. *Asian Journal of Education and Social Studies, 14*(4), 1-12. https://doi.org/10.9734/ajess/2021/v14i330359

Anderson, J. A. (2003). The challenges of collaborative knowledge. *Learning objects: contexts and connections*, 1-15.

Bell, C. V., & Pape, S. J. (2012). Scaffolding students' opportunities to learn mathematics through social interactions. *Mathematics Education Research Journal, 24(4)*, 423-445. https://doi.org/10.1007/s13394-012-0048-1

Chee, K. N., Yahaya, N., & Ibrahim, N. H. (2018). An evaluation of the learning effectiveness of a formulated ideal social collaborative mobile learning environment application towards cognitive level in biology. *International Journal of Mobile Learning and Organisation*, *12*(2), 62-189. https://doi.org/10.1504/IJMLO.2018.090850

Chen, J., Wang, M., Kirschner, P. A., & Tsai, C. C. (2018). The role of collaboration, computer use, learning environments, and supporting strategies in CSCL: A meta-analysis. *Review of Educational Research, 88*(6), 799-843. https://doi.org/10.3102/0034654318791584

Chiuphae, P. (2023). Cooperative learning management using jigsaw puzzle techniques to promote achievement in learning democracy for grade 1. In *Proceedings of the International Academic Multidisciplinary Research Conference in Zurich* (pp. 213-218).

Cirillo, M. (2013). *What are some strategies for facilitating productive classroom discussions?* Research Brief 20, National Council of Teachers of Mathematics.

Durlak, J. A., Weissberg, R. P., Dymnicki, A. B., Taylor, R. D., & Schellinger, K. B. (2011). The impact of enhancing students' social and emotional learning: A meta-analysis of school-based universal interventions. *Child Development, 82(*1), 405-432. https://doi.org/10.1111/j.1467-8624.2010.01564.x

Fuchs, L. S., Espinas, D. R., & Seethaler, P. M. (2023). *Fourth-Grade Fractions Battery*. Technical Report. Vanderbilt University

Huang, H. W., Wu, C. W., & Chen, N. S. (2012). The effectiveness of using procedural scaffoldings in a paper-plus-smartphone collaborative learning context. *Computers & Education*, *59*(2), 250-259..

Johnson, R. T., and Johnson, D. W. (1985). Relationships Between Black and White Students in Intergroup Cooperation and Competition. *Journal of Social Psychology. 125*(4), 421-428.

Johnson, D. W., & Johnson, R. T. (2014). Cooperative learning in 21st Century. *Anales de Psicologia [Annals of Psychology], 30*(3), 841-851. https://doi.org/10.6018/analesps.30.3.201241

Jones, S. M., Brush, K. E., Ramirez, T., Mao, Z. X., Marenus, M., Wettje, S., Finney, K., Raisch, N., Podoloff, N., Kahn, J., Barnes, S., Stickle, L., Brion-Meisels, G., McIntyre, J., Cuartas, J., & Bailey, R. (2021). Navigating Social and Emotional Learning from the Inside Out (2nd ed.). The Wallace Foundation. https://wallacefoundation.org/sites/default/files/2023-08/navigating-social-and-emotional-learning-from-the-inside-out-2ed.pdf

Laal, Marjan & Ghodsi, Seyed. (2012). Benefits of collaborative learning. *Procedia - Social and Behavioral Sciences 31*, 486 – 490. https://doi.org/10.1016/j.sbspro.2011.12.091

Le, H., Janssen, J., & Wubbels, T. (2017). Collaborative learning practices: teacher and student perceived obstacles to effective student collaboration. *Cambridge Journal of Education*, *48*(1), 103–122. https://doi.org/10.1080/0305764X.2016.1259389

Lee, K., Tsai, P. S., Chai, C. S., & Koh, J. H. L. (2014). Students' perceptions of self‐ directed learning and collaborative learning with and without technology. *Journal of Computer Assisted Learning, 30*(5), 425-437. http://dx.doi.org:/10.1111/jcal.12055

Mayer, R. E., Stull, A., DeLeeuw, K., Almeroth, K., Bimber, B., Chun, D., M. Bulger, J. Campbell, A. Knight, & Zhang, H. (2009). Clickers in college classrooms: Fostering learning with questioning methods in large lecture classes. *Contemporary Educational Psychology, 34*(1), 51–57. https://doi.org/10.1016/j.cedpsych.2008.04.002

Muis, R. R., Chevrier, M., & Singh, C. (2018). The role of epistemic emotions in personal epistemology and self-regulated learning. *Educational Psychologist, 53*, 165-184. https://doi.org/10.1080/00461520.2017.1421465

National Center for Education Statistics. (2022). The Nation's Report Card: 2022 Mathematics and Reading Assessments. U.S. Department of Education, Institute of Education Sciences. https://www.nationsreportcard.gov/mathematics/nation/achievement/?grade=4

OECD (2014). Scaling procedures and construct validation of context questionnaire data. *PISA 2012 Technical report*.

OECD. (2016). *Innovating education and educating for innovation: The power of digital technologies and skills*. OECD Publishing. https://doi.org/10.1787/9789264265097-en

Prince, M. (2004). Does active learning work? A review of the research. *Journal of Engineering Education, 93*(3), 223-231.

Roschelle, J., Rafanan, K., Bhanot, R., Estrella, G., Penuel, B., Nussbaum, M., & Claro, S. (2010). Scaffolding group explanation and feedback with handheld technology: Impact on students' mathematics learning. Educational Technology Research and Development, 58(4), 399–419. https://doi.org/10.1007/s11423-009-9142-9

Schreiber, L. M., & Valle, B. E. (2013). Social constructivist teaching strategies in the small group classroom. *Small Group Research, 44*(4), 395-411. https://doi.org/10.1177/1046496413488422

Siller, H.-S., & Ahmad, S. (2024). Analyzing the impact of collaborative learning approach on grade six students' mathematics achievement and attitude towards mathematics. *Eurasia Journal of Mathematics, Science and Technology Education, 20(2)*, em2395. https://doi.org/10.29333/ejmste/14153

Suliswaro, D., & Syarif, F. (2018). The utilization of open educational resources in the collaborative learning environment to enhance the critical thinking skill. *International Journal of Learning and Development*, *8*(1), 73. https://doi.org/10.5296/ijld.v8i1.12399

Tolmie, A., Topping, K., Christie, D., Donaldson, C., Howe, C., Jessiman, E., Livingston, E., & Thurston, A. (2010). Social effects of collaborative learning in primary schools. *Learning and Instruction, 20,* 177–191. https://doi.org/10.1016/j.learninstruc.2009.01.005

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