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CASE STUDY

Navigated learning: An approach for differentiated classroom instruction built on learning science and data science foundations

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Abstract

Classroom teachers are often provided with instructional resources and assessment systems that dictate one pathway for every student's learning and evaluation. These practices remain common despite new affordances available through data-rich, emerging digital technologies that draw on data science and learning science foundations to complement and enhance traditional instruction. This paper presents a conceptual framework for Navigated Learning, a pedagogical approach that operationalizes learning principles using emerging ideas in artificial intelligence and data science, resulting in the continuous, real-time generation of students' cognitive and noncognitive data to support a teacher's ability to utilize the system to customize instruction. The paper articulates the learning principles underlying the pedagogical approach and the features afforded by the Learning Navigator system. The paper concludes with two cases of very different implementation of Navigated Learning focused on fifth grade and ninth grade students' learning of mathematics.

KEYWORDS

academic, adolescents, artificial intelligence, big data, collaborative learning, e-learning, engagement, human cognition, human-computer, human development, human social behavior, interaction, mobile, online communities, performance, students, technology

1 | INTRODUCTION

A great deal of K-12 classroom-based learning functions within a set of structures reinforces traditional norms and practices. For example, although students are grouped by age rather than ability, curricular sequences and assessments are often identical for all learners regardless of ability or preference, and instructional approaches emphasizes cookbook laboratories or computation using formulas rather than critical thinking or problem solving. Research studies also demonstrate that traditional instructional approaches, such as lectures, and traditional instructional resources, such as textbooks, are prevalent in both university-level Science, Technology, Engineering, and Mathematics (STEM) courses (Stains et al., 2018) and secondary instruction (e.g., National Research Council [NRC], 2019).

These practices remain common despite research results, providing strong evidence that more active learning approaches, such as even occasional problem solving or the use of personal response systems, lead to stronger learning outcomes (e.g., Freeman et al., 2014). For example in science, recent reviews provide evidence of stronger learning outcomes when instruction is focused around local phenomena, science investigations, or engineering design projects with problem-solving dimensions (e.g., Furtak, Seidel, Iverson, & Briggs, 2012; NRC, 2019).

Globally, American students underperform in STEM areas, including mathematics. The Programme for International Student Assessment (PISA) mathematics is an international assessment, which provides evidence of 15-year-olds' abilities worldwide to formulate and interpret mathematics in variety of problem-solving contexts

(Organization for Economic Co-operation and Development [OECD], 2015). On PISA mathematics, American students ranked below the OECD average at 35/44. Economic analyses inform us that a growing proportion of jobs are concentrated in STEM fields and that economic growth and financial stability are connected to STEM education systems (OECD, 2019). Policy documents also reveal that even as many young adults are unemployed or underemployed, there is a shortage of high-skilled workers with the training needed for jobs of the future. Employers state that future workers need to be: (a) digitally skilled with the ability to continuously refresh their knowledge and skills, (b) fluent in critical thinking and collaboration, and (c) able to take ownership of their own learning (Pompa, 2015). Globalization has resulted in multilingual and multicultural learners with diverse knowledge and interests, many of whom have largely not been allowed to experience learning opportunities to meet these new demands. In sum, research and policy analyses suggest that to be globally competitive, we need strong K-12 STEM education programs that support problem-based, active learning-focused, and differentiated instruction.

Far too often, classroom teachers are provided with instructional resources and assessment systems that dictate one pathway for student learning and evaluation. In other words, a great deal of classroom instruction is focused on getting all students in the same class to the same "destination"–that is, the standards, curricular, or assessment metrics that we expect students to demonstrate proficiency on by the end of the course. Differentiated instruction is the presentation of customized and adaptive curricula optimized for each learner's knowledge, skills, abilities, and interests (Tomlinson et al., 2003). With the high degree of academic, cultural, and linguistically diverse populations in American classrooms, teachers face enormous challenges to provide meaningful, differentiated instruction to all students. As stated by Tomlinson et al., "While heterogeneous instruction is attractive because it addresses equity of opportunity for a broad range of learners, mixed-ability classrooms are likely to fall short of their promise unless teachers address the learner variance such contexts imply. In such settings, equality of opportunity becomes a reality only when students receive instruction suited to their various readiness levels, interests, and learning preferences, thus enabling them to maximize the opportunity for growth (Tomlinson et al., 2003, p. 120).

Emerging digital technologies present both an incredible opportunity and new challenges in many contexts (Yan, Gaspar, & Zhu, 2019), including classroom learning. Advances in artificial intelligence and data science afford new possibilities for teacher customization and differentiation of learning. As stated by Collins and Halverson (2010), "While the industrial revolution gave rise to a universal schooling system where none had previously existed, the information technology revolution presses a very real, active system to reconsider its fundamental practices" (Collins & Halverson, 2010, p. 18).

It is not surprising that realizing the opportunities afforded by emerging digital technologies is not straightforward. While emerging technologies have been available for several years, few learning systems exist that provide such affordances to address the challenges of differentiated instruction in today's classrooms. One system, Carnegie Learning's Cognitive Tutor, uses frequent assessments to offer individualized learning similar to a tutoring experience. The Cognitive Tutor implements cognitive science principles into the system to promote efficient student learning and engagement. Research results demonstrate that learners are a grade level ahead of students who engage in more traditional learning approaches (Ritter, Anderson, Koedinger, & Corbett, 2007). i-Ready empowers teachers and students with data to help take ownership of learning and to differentiate instruction. The diagnostic and assessment reports support teacher decisions to help students gain proficiency. A case study of an elementary school in northwest Florida implementing all aspects of the i-Ready suite saw student proficiency increase from 52 to 59% as an overall school score, which is just shy of earning a top-rated school credential (i-Ready, 2018).

While these tools and a handful of others have demonstrated some promising early outcomes, we propose that collectively, classroom-focused emerging digital technologies have not realized significant impact on the productive differentiation of classroom learning. Why? One explanation is that previous designs did not sufficiently take into account the human side of research on emerging digital technologies, including the ways in which technology could support the classroom teacher's ability to differentiate learning amidst a classroom of unique learners. As stated eloquently by Yan et al. (2019), "While humans develop and use technologies, technologies significantly influence humans in extremely complex ways (e.g., mobile phones enhance communications and, at the same time, facilitate constant distractions). As no one could deny the importance of developing technologies, more responsible scientists and the general public have come to realize the critical need to better understand the *human side* of emerging technologies rather than just the *technical side* of traditional technologies… Through productive interdisciplinary research, we are able to see more clearly the extreme and rich complexity of human behaviors with various emerging technologies" (Yan et al., 2019, p. 1, 2).

Our work represents research and development that interweaves theory and empirical studies into interdisciplinary research that includes the learning sciences, data science and artificial intelligence, for example, research work focused on both the human and the technical sides of emerging digital technologies for learning. The paper presents a conceptual framework for Navigated Learning, a pedagogical approach that operationalizes learning principles using emerging ideas in artificial intelligence and data science resulting in the continuous, real-time generation of students cognitive and noncognitive data. The system utilizes a learning data backbone, that is, data and information from online and offline learning, to support customized and informed decision-making by teachers or greater ownership and monitoring of one's own learning whether it is occurring in online or offline settings. The paper also presents empirical results to address the question, How did different teachers integrate Navigate Math into their classroom, and what evidence of learning was demonstrated? The paper concludes with data and examples from the implementation of in the Learning Navigator in two-fifth grade and two-ninth

grade classes of students learning mathematics in diverse schools in Northern California, USA.

2 | WHAT IS NAVIGATED LEARNING?

The focus of our work is interdisciplinary research that goes beyond merely the design of a data-rich backbone (e.g., the technical side) to include the design and examination of an educational approach (e.g., the human side of emerging digital technologies). Navigated Learning is a pedagogical approach with foundations in the learning sciences that are made operational through data science. In other words, Navigated Learning is realized when fundamental principles of learning are identified and operationalized within a data-rich technology system called the Learning Navigator. The system realizes continuously updated information on each student's customized learning pathway.

2.1 | The learning navigator

The data-rich technology system, the Learning Navigator, is comprised of three technology enablers (see Figure 1). These are: (a) the Navigator Competency Model (NCM), which organizes the learning space, (b) the Learning Data Backbone, which captures continuous data in real time and informs the suggestions and re-routes, and (c) the Learning Apps, which include all of the resources and intelligent components that present a differential interface for each stakeholder (e.g., students, teachers, and administrators).

NCM is the conceptual model and framework for the Navigator system. The term Competency is synonymous with a cognitive learning standard or a noncognitive attribute, such as critical thinking or creative thinking. Competencies are linked by metadata tags organized by domain, depth of learning, and tags associated with the other vectors of learning into a three-dimensional dependency graph. The *x*-axis provides tags for the domain, the *y*-axis provides tags for the pedagogy level and depth of learning (e.g., fifth grade, analyze patterns, and relationships), and the *z*-axis provides tags associated with other vectors, such as the noncognitive information and skills. Competencies are often associated with existing structures, such as the Common Core Mathematics standards (National Governors Association Center for Best Practices, & Council of Chief State School Officers, 2010). Standards from different states, countries, and organizations are cross-walked to identify overlap and to develop a robust and inclusive model. Competencies also have metadata and learning activities associated with it and information regarding proficiency (e.g., student struggles or depth of knowledge of the competency). The collective set of resources and tags organized by the framework become central components of the (Learning) Navigator system.

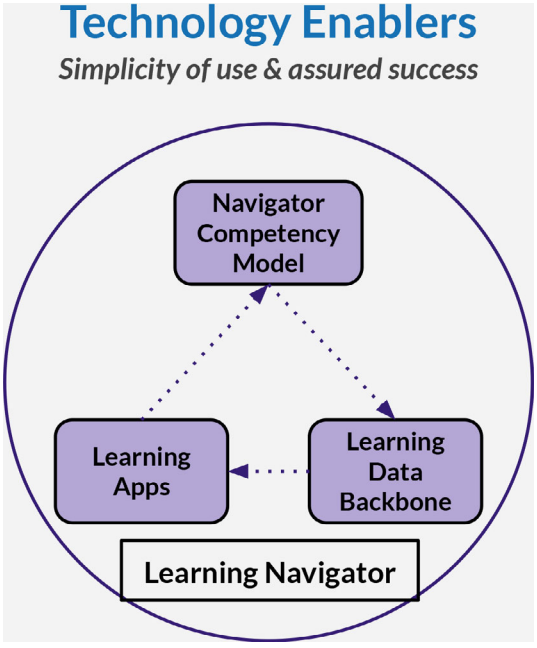

FIGURE 1 The three technology enablers of the Learning Navigator

The Learning Data Backbone is the rich and complex set of data collected when students and teachers interact with the system resulting in continuous updates on the student, teacher, and catalog information. As mentioned, all learning resources and assessments in the Navigator are aligned to competencies with many metadata tags. Each interaction within the system results in newly created links between user information and resources. Metadata are computed from the activity stream data and the efficacy of the learning activities are measured against the competencies mastered using information from the catalog. Once the system has complete activity stream data from a set of learner's interactions, the system computes learner vectors to continuously update a more precise location of the learner. A similar process exists to operationalize the learning principles. The interaction of the learner with the system creates a data activity stream. This then informs the action suggested to the learner based on the learning principles.

The learning data backbone underlies the Learning Apps for students, teachers and administrators (collectively referred to as Users). The Apps focus on providing the stakeholders data, analysis, and suggestions using open educational resources. Users can then make decisions toward achieving learning outcome gains on the competencies that the student needs to learn. Navigated Learning enables a variety of providers the ability to bring content, tools and implementation services to benefit a number of users including their own prioritized students, teachers, parents, and/or administrators.

2.2 | Four elements of navigated learning

As mentioned, Navigated Learning is a pedagogical approach with foundations in the learning sciences. Navigated Learning is premised on the principle that effective guiding and supporting of learners begins with the gathering and organizing of the data and information made available by the Technology Enablers. Data organization and application towards student learning is accomplished through the four elements of Navigated Learning (see Figure 2). The first element, Locate, refers to the set of competencies, metatags, rules, and

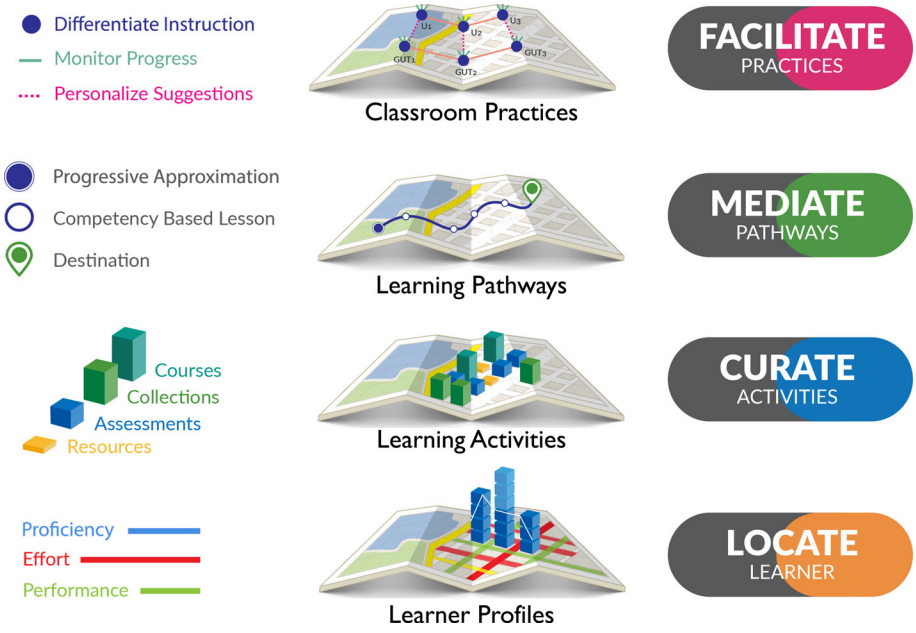

FIGURE 2 The four elements of Navigated Learning: Locate the learner, Curate activities, Mediate pathways and Facilitate practices

TABLE 1 Cognitive competency from Common Core Mathematics Common Core Standards Initiative (2010) with student display name, common struggles on the competency, hint and solved example

Competency	Student display name	Struggle	Hint	Solved example from open education resource
6.NS.6.a: Recognize opposite signs of numbers as indicating locations on opposite sides of 0 on the number line; recognize that the opposite of the opposite of a number is the number itself, for example, –(–3) = 3, and that 0 is its own opposite.	Recognize numbers and opposites on a number line	Recognize numbers and opposites on a number line	Show the number line as a visual and have the learner count to zero from each location. Give a short scenario showing the opposites added together become 0	https://www.varsitytutors.com/hotmath/hotmath_help/topics/integers

interactions that result in the designation of a real-time, successive approximation of a "location" of the learner's current knowledge, skills, and noncognitive attributes at any learning time and place. In other words, in order for a teacher, a learning system or a student to guide learning, the Navigator system and the Users must gather and organize successive approximations of what knowledge and preferences each learner has and has not demonstrated. In Locate, the system uses machine learning techniques to precisely locate the learner based on data about the learner's knowledge, skills, and noncognitive data, such as the student's interests. Recognizing that any characterization of a learner is always an imperfect approximation of what an individual actually knows and likes, the system filters and organizes continuously generated and updated data for increasingly improved successive approximations of location (Diwan, Srinivasa, & Ram, 2018).

In Locate, proficiency information is gathered at the competency level. Student struggles and depth of knowledge are identified at each competency. Struggles refer to areas where student errors or alternative ideas are common. When a student demonstrates a common struggle in response to a particular assessment item, the system will generate a Hint and Solved Examples from open education resources (OER) to guide the learner in next steps to continually update the learner's location. Table 1 provides an example of a cognitive competency from Common Core Math Standards and resources associated with each competency. For each competency, the design team creates a Student-friendly Display Name.

Competencies can be organized into an instructional sequence (i.e., Learning Pathway) by either the metadata tags themselves (e.g., Common Core Standards), or through customization by the teacher or student. A competency will generally also be identified with a prerequisite list of competencies that need to be acquired in order to be able to engage successfully with the focal competency.

Once the collective set of metadata and tags are assigned for each competency, the Locate element of Navigated Learning uses the learner's interactions with these metadata and tags to continuously characterize and represent a learner's highest level of competency

within a given Learning Pathway. A learner's Skyline is the continuously updated set of maximum data values per domain that students have demonstrated within the system (see Figure 3, green line). Each Skyline represents a student's competencies in the three-dimensional metric space. The green line represents the grade line, for example, the end destination of that learning pathway for that course. Subjects can be a core curriculum, noncognitive skill or vocational skill. At any given moment, the teacher or student can identify a student's aggregate competency level, for example, the students' Skyline, by looking at the line connecting the competency levels of a collection of competencies in a given Learning Pathway.

The second element of Navigated Learning is Curate. Curate refers to the metadata tagged and computed (e.g., efficacy) for the set of on and offline resources. Courses are a set of multiple collections and assessments that span across multiple grade levels. An example Course may include Math competencies between grades 5 and 8. Collections are playlists of resources within a competency which give multiple contexts to the content to encourage deep learning. Resources include a full spectrum of learning activities, which encompass digital and offline tasks done individually or in groups. Digital resources include simulations, games, videos, and webpages. Offline resources include projects, long answer responses, and proofs, which are supported by rubrics and other activities, such as field trips, presentations, and working with manipulatives.

Assessments come in several forms. Course Assessments include machine graded items as well as offline short answer and project-based tasks scored using rubrics. The Course Assessments are designed to establish evidence of proficiency of the competency at different depth of knowledge levels within the Learning Pathway. Additionally, Signature Assessments are offered to students as a suggestion and ask students to think more critically and apply their knowledge demonstrating a greater complexity of understanding.

Assessment data can be entered into the system in a variety of ways, including through direct entry or through photo-entry of offline or rubric-coded material. To Curate the different types of resources within Courses, resources are tagged with metadata such as competencies, depth of knowledge, student struggles, and types of resources.

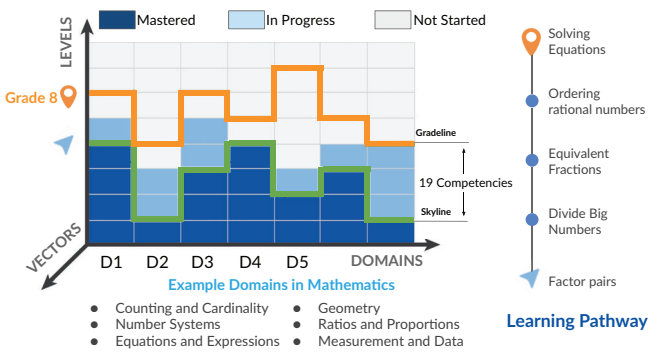

FIGURE 3 Three-dimensional Skyline

Live Assessments are continuous assessments used for formative purposes, that is, to adjust teaching and learning. Live Assessments enable teachers to monitor students' progress, track individual and class responses in real time, and then differentiate their instruction accordingly. Live Assessments can also be customized by teachers. Figure 4 presents two views of Live Assessments. Students can check for their own understanding and build key skills including developing understanding of their own learning, setting goals, reflection, and giving and receiving feedback. Individual student and whole-class responses are tracked in real time, allowing teachers to differentiate instruction and provide immediate intervention to every student. The teacher can easily give different Live Assessments to different learners to fill gaps, reinforce knowledge, and extend knowledge development. Teachers are encouraged to use Live Assessments frequently or however they fit into classroom norms.

The third component of Navigated Learning is Mediate. Mediate refers to the system's use of data, rules, and resources to interpret a location for a learner and suggest new resources or assessments for a learner's next activity, that is, the technical side (Yan et al., 2019) of our classroom-focused, emerging digital technology. Mediate draws on the operationalization of Learning Principles. The following sections outline the process of selecting and operationalizing learning principles within the Learning Navigator.

Drawing from research on how people learn (e.g., NRC, 2000, 2018), the design team identified five learning principles to operationalize in the Navigator to guide the delivery and sequencing of suggestions and resources. Each principle was selected because it has been verified through both established and current research foundations. For example Principle 1 states, *Students learn best when they are actively engaged in constructing new learning on a foundation of prior knowledge and experience*. This principle builds from established ideas about the importance of building on prior knowledge (e.g., from How People Learn; NRC, 2000) as well as more recent ideas about the influence of cultural, physical, and social factors that influence the current learning experience (e.g., NRC, 2019). Similarly, Principle 3 builds from established ideas on the importance of the guidance and revisiting of ideas through a variety of interactions and contexts to support deep conceptual understandings and the possibility of knowledge transfer (e.g., NRC, 2000) as well as more recent research supporting the value of targeted feedback to foster deep conceptual understandings and metacognition (e.g., NRC, 2018). Table 2 illustrates the five learning principles and representative literature that supports each principle.

After learning principles were identified, the design team established a set of models for the operationalization of the learning principles called Event Condition learning Principles and Action (ECPAs). These models "listen" to events and based on the condition about a learner, the models trigger actions which are suggestions based on the learning principles associated with the model. Table 3 illustrates four ECPAs associated with decision-making in the Navigator. By operationalizing the learning principles, the suggestions and actions offered to the students are backed by learning theories and

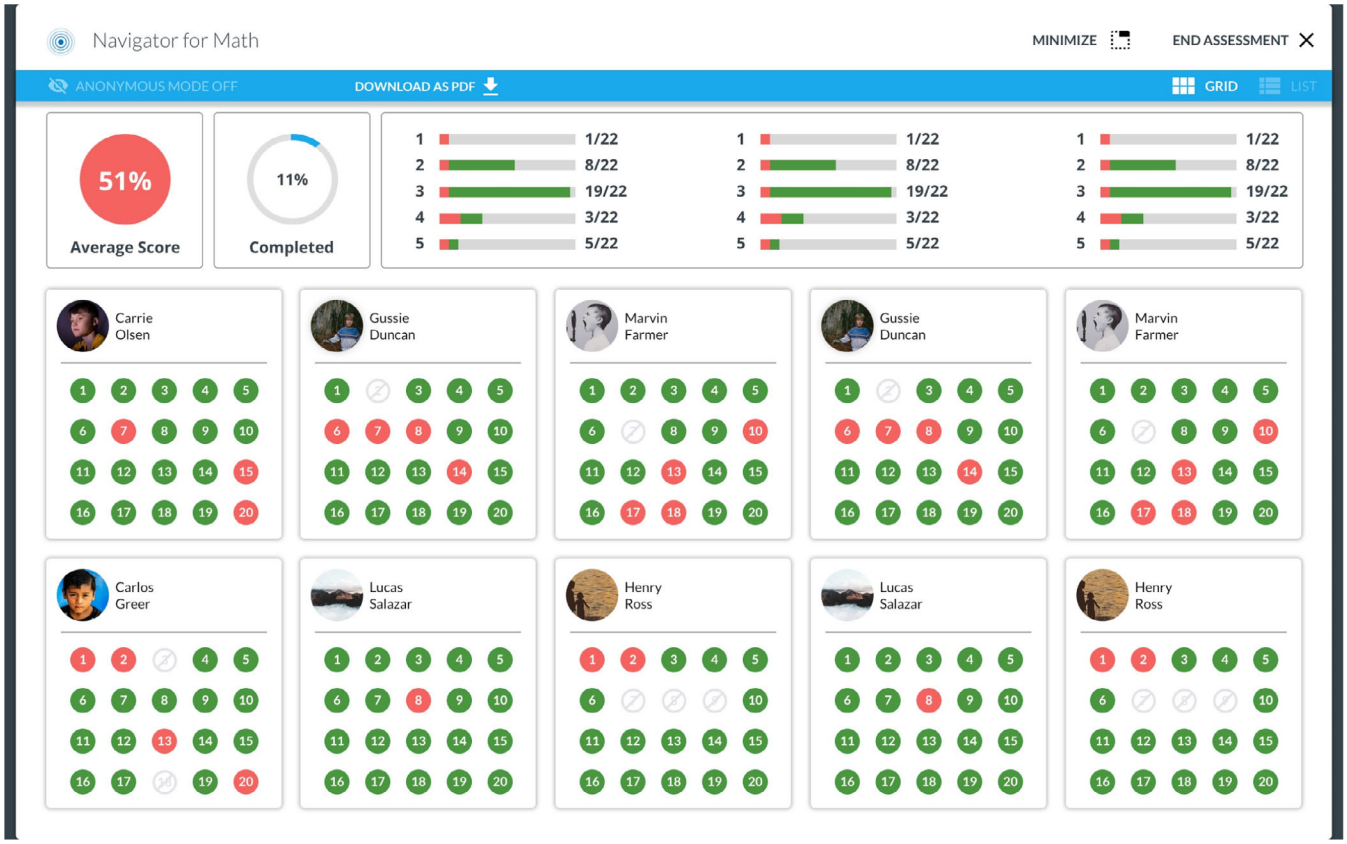

FIGURE 4 Dashboards from Live Assessments show the answers that students got correct and incorrect in real-time. This image shows data by student (green if correct and red if incorrect). The teacher can click any question number to see a specific student answer. The high level overview allows the teacher to review a question that posed problems or for other reasons. Teachers can also quickly get a big-picture view for individuals or groups by color. Other views can sort by ascending and descending scores, time spent on each task, and student reactions as an emoji for each item

TABLE 2 Five learning principles selected for operationalization in the Navigator system

Learning principles
Principle 1: Students learn best when they are actively engaged in constructing new learning on a foundation of prior knowledge and experience (e.g., NRC, 2000; NRC, 2018)
Principle 2: Students learn best when their learning opportunity is a stretch learning experience; e.g., it builds on what they know and provides guidance but also extends or applies what they know in a new way, whether that extension is to a new context, a chance for them to make an inference, an analogy, or to a surprising next step (e.g., Vygotsky, 1978; NRC, 2019).
Principle 3: Students learn best when they have the opportunity to revisit an idea or concept multiple times, including revisiting in response to feedback and when revisiting is new flavors or variations on the original (e.g., Bruner, 2009; Reiser, 2004).
Principle 4: Assessment is always an imperfect measure of what someone knows. Therefore, frequent embedded assessment, multiple levels of challenge and multiple kinds of evidence are the best means to generate a solid estimate of progress of critical thinking, knowledge and skills (e.g., Bransford et al., 2005).
Principle 5: Choice, within reasonable limits and with supports, fosters engagement, confidence-building, and perseverance. Learning environments that foster trust and risk-taking with guidance foster deeper engagement, confidence-building, and perseverance (e.g., National Research Council, 1987).

science. Figure 5 shows the flow chart of ECPA ending in the suggestion informed by the learning principles.

To train the algorithm to operationalize the learning principles, each component of the ECPA table needs to be defined and fully understood. To identify and define learning/learner conditions, user journeys and maps were created through user interviews as well as user pathways within the system (Diwan et al., 2018). The process allowed for a more complex understanding of the condition of the learners. This helped to build out the different conditions that will most likely exist within system interactions. For example, conditions included a spectrum of struggling learners to students who need additional challenges to extended knowledge. Additionally, other conditions can include variations in technology within the classroom (e.g., 1:1 technology versus only the instructor having a smartphone).

TABLE 3 Example event, condition, learning principles & action (ECPAs)

Event	Condition	Action
Performs poorly in an assessment	Good student with proficiency in dependent competencies	A suggestion to reinforce concepts & extend learning
Performs well in an assessment	Shows proficiency but demonstrates an alt concept/struggle on a question	Offer worked out example of struggle, move forward in learning and offer review problem in near future
Performs poorly in an assessment	Student with gaps in prerequisite competencies and tests slightly below grade level	Fill gaps in learning and engage in constructing knowledge
Displays common alternative conception multiple times on assessments	Student on grade level with common struggle areas	Suggest additional resources and practice problems with solved examples to see struggle areas in new contexts

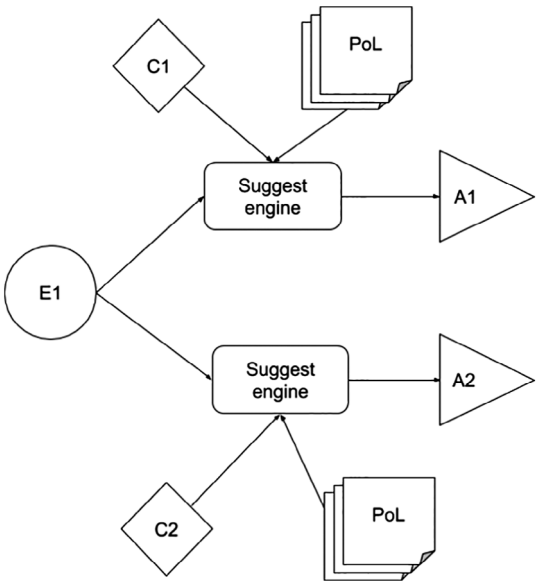

FIGURE 5 A flow chart for event, condition, learning principle, and actions. Each event, condition and overlying learning principles go into the suggestion system to help determine the action suggested to the learner. The process starts with an event triggered by a student interaction with the system. Each event has a condition associated with it. There can be one to several learning principles that are triggered from the event and condition to then determine the action suggested to the student

Independently a list of possible events that can occur were listed. The events included interactions with resources, assessments, and taking suggestions. These could be both online and offline rubric graded items. Example events included: failing or succeeding on an assessment, displaying common struggles on assessments, and taking or turning down assessments. For each condition, every event is listed and different possible actions are offered. The underlying learning principles guided actions that were suggested based on the events and conditions The actions included: suggestions in the form of additional resources, assessments to earn badges, scaffolds/hints, solved examples.

The fourth element of Navigated Learning is Facilitate. Facilitate refers primarily to the human side (Yan et al., 2019) of the design and realization of our emerging digital technology in classroom settings. In other words, Facilitate refers to the set of interactions, classroom practices, and activities that teachers realize in association with the data and resources within the Navigator system in order to monitor progress and personalize suggestions. In Facilitate, the teacher plays a critical role in differentiating instruction using data offered by the system. For example, Suggest in Facilitate provides real-time data to the teacher who then uses these data to offer suggestions to the student.

The teacher's dashboard has high-level views that illustrate proficiency and progress as well as an ability to do a deep dive by student and domain and standard. Three views of data and information from the Teacher Dashboard are illustrated in Figure 6. As seen in these views, teachers are able to analyze data in the moment and obtain information to guide individual work with students, organize pairs or small groups, or otherwise tailor instruction to student needs. Teachers are also able to monitor and adjust instruction for the whole class based on data covering student engagement, performance, and proficiency. In the dashboard showing Course Activities, teachers see results from the Live Assessment, which provide real-time data regarding student answers, time on each problem, and student reactions to questions. This dashboard allows a quick review of a challenging problem and/or confirmation if a concept and skills was well understood and by which students. From the data, teachers can make suggestions to individual students, such as offering extra resources to see content in a new context or more challenging practice problems to aid in extending knowledge development.

For students, the Navigator also provides valuable, real-time feedback through data reports and a competency-based proficiency dashboard. Students can view reports at any time to see their engagement, performance, or reaction to any content they have studied. Students are also able to view their personalized proficiency dashboard to analyze their competency progress and see the scores on assessments, time spent on collections and assessments, and proficiency by competency.

In summary, the four elements of Navigated Learning articulate the dimensions of our interdisciplinary system that take into account both the technical and the human side of emerging digital technologies in real settings. The four elements work in concert to support the possibility of greater differentiated learning. The following two cases

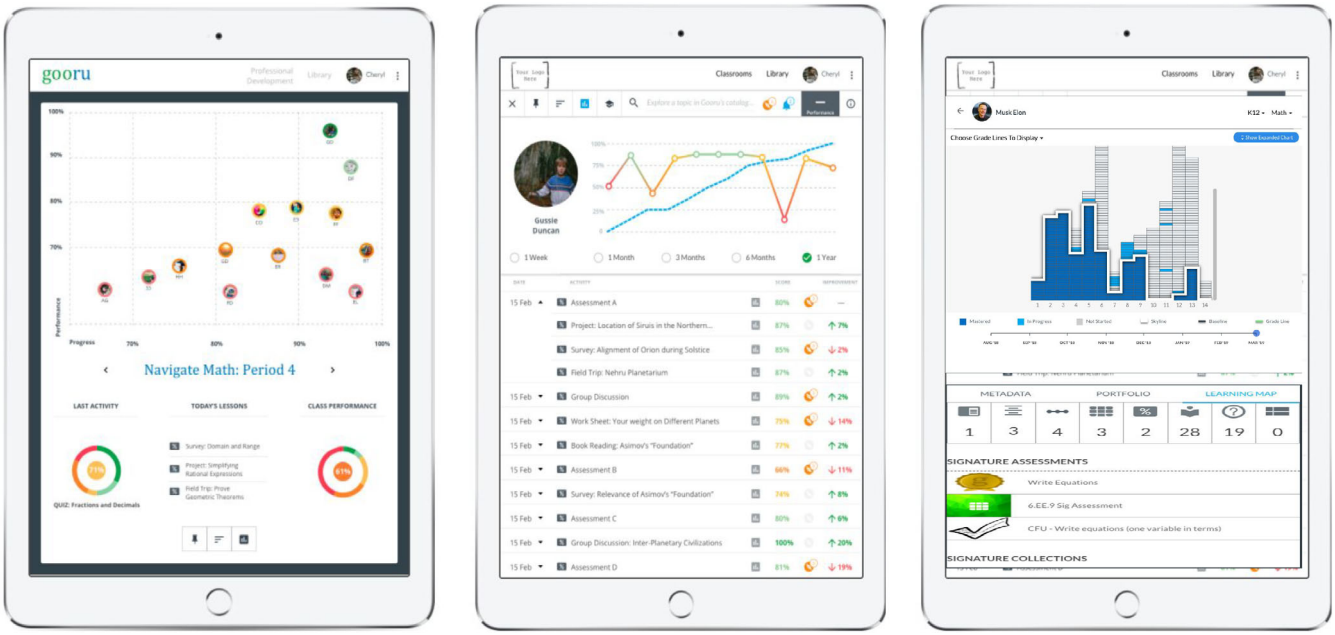

FIGURE 6 Teacher dashboards. On the left, teachers see a high level overview of students' proficiency on course material. In the middle, the class roster view includes suggestions to give the students based on a student's performance on an assessment. The teacher can visualize the data over different periods of time. On the right, the teacher visualizes a student's skyline and can track competencies gained and in progress over time. The teacher can make suggestions in areas of demonstrated struggle or gaps

present illustrations of how Navigated Learning was used with two different populations of students and teachers.

3 | HOW ARE STUDENTS AND TEACHERS USING NAVIGATED MATH?

To evaluate the Navigator system and the Navigated Learning pedagogical model, we implemented one Navigator course, Navigate Math, within two different classroom settings in diverse Northern California classrooms.

3.1 | Methods

We conducted case study research to address the question, How did different teachers integrate Navigate Math into their classroom, and what evidence of learning was demonstrated? This question was addressed through data analysis associated with classrooms that utilized Navigate Math in conjunction with their classroom Common Core mathematics curriculum over a 3-month time period. Case 1 is all of the fifth grade students in a K-8 school in Northern California where 55% of the students received free or reduced lunch and 23% of the students were English Language Learners. On state testing, 64% of students were below grade level on math in 2017. Case 2 is two classes of ninth grade students who were at least three grade levels behind in mathematics. The school was located in a bedroom community of a large city on the west coast. The students were described by administrators as having a bimodal distribution of achievement. There are 4,900 students in K-12, where 46% are minority students and 19% are on free or reduced lunch. On 2017 California Assessment of Student Performance and Progress tests, 44% of learners did not meet math standards for achievement (see Table 4).

3.2 | Navigated math instructional materials

Navigate Math is a course that was developed using OERs around the 268 Common Core Math Standards for grades 2–8. Navigate Math covers all Common Core Standards in 10 domains (Operations and Algebraic Thinking, Number and Operations in Base Ten, Number and Operations—Fractions, Measurement and Data, Geometry, Ratios and Proportional Relationships, The Number System, Expressions and Equations, Functions, Statistics and Probability) and all eight Mathematical Practices. Learning Pathways for all of the standards within these domains were identified and tagged to support a set of resources and content that met teacher and district goals. Navigate Math instructional materials and assessments were organized using the structure of the Navigator Competency Model (e.g., Subject, Course, Domain, Competency, and Concepts).

While the backbone content within the system was drawn from OERs, teachers and students were encouraged to bring in other content, projects, and practices to support learning from their existing district approved curriculum and then take assessments in the system to track learning and proficiency. The metadata tags, including tags on standards and depth of knowledge, continuously updated information available to both the learner and teacher so that each could make informed and focused decisions to promote learning. The instructional materials were organized to create a flexibility to be variously adapted to a range of

TABLE 4 Classroom demographics and implementation notes for Navigate Math cases

	Number students	Demographics	Prior math ability	Implementation of Navigate Math
Case1: Two classes of fifth grade students	57	3,600 K-8 students 55% FRL 23% ELL	Range of learners from low to high achieving	Used Navigate Math on Wednesday math periods plus when they completed other classwork throughout the week
Case 2: Two classes of ninth grade students	36	4,900 K-12; 46% minority, 19% FRL	Remedial math students who are 3–5 grade levels behind	Students worked on Navigate Math 3–4 times per week independently and as a whole class using class activities

implementation models as desired by teachers in different classrooms and with different audiences and goals. When learners were working on activities tied to Common Core Standards, teachers and students could observe real-time data to make suggestions or follow suggestions to review or extend the learning, such as to try more challenging content.

3.3 | Navigate math assessment materials

The Navigate Math assessment system provided a series of organized, embedded assessments that provided data to the Navigator system to continually update a learner's Skyline. To track student progress and proficiency, learners took Course Assessments within the course map along each learner's personalized Learning Pathway. All assessments in the course were mapped to competencies. The assessments within the Navigate Math course were also designed to assess conceptual understandings. Course Assessments were typically five to seven questions that cover depths of knowledge one through three (Webb, 2002). Webb's depth of knowledge is on a scale of 1–4 where level 1 is recall, level 2 is skills and concepts, level 3 is short-term strategic thinking, and level 4 is extended thinking. In addition, students interacted with embedded Course Assessment items which were used to identify gaps in student proficiency, and to confirm an accurate diagnosis of student performance. The Navigate Math proficiency was defined as follows: If a learner earned >80% on a Course Assessment, the student's Skyline indicated proficiency for that competency and the student was offered an additional in depth Signature Assessments to demonstrate a greater depth of knowledge on the competency. If a student earned less <80% on the Embedded Assessment, an additional highly curated collection was suggested that was targeted to the gaps identified from the assessment.

3.4 | What did professional development look like?

Teacher training was essential to ensure teachers were comfortable in using the Navigator to foster Navigated Learning. All Navigate Math teachers participated in 16 hr of an introductory face-to-face professional development course with other teachers in their school to provide a community of support and collaboration. During the initial training, teachers were introduced to the student and teacher dashboards of The Learning Navigator. Teachers spent time interacting with Navigate Math as a student to understand the system's features and best means to work with the data for differentiation of student learning. Time was spent viewing and analyzing different data patterns that they will see with their students. At the end of training, teachers spent time lesson planning to ensure that their implementation of the Navigate Math would fit well with their existing classroom norms and practices.

There were also 15 hr of additional planning and check-in meetings during the first days of implementation. These hours focused on how teachers could support and tailor each learner's initial Learning Pathways that were established using Northwest Evaluation Association (NWEA) Measures of Academic Progress (MAP) scores as a first approximation of the student Skyline.

Teachers also received weekly check-in calls from the technical and professional development support team of the research project to review successes and struggles. Furthermore, detailed weekly metrics were shared with each teacher and students at each school. Feedback from teachers and students also provided essential real and near-time information on many aspects of the usability of the Navigate Math system. In total, teachers received approximately 30 hr of professional development and support associated with the 3-month implementation of Navigate Math in their classrooms.

4 | IMPLEMENTATION, DATA ANALYSIS AND RESULTS

4.1 | Case 1: Fifth grade navigate math Wednesdays

The fifth grade teachers in Case 1 established Navigate Math Wednesdays as a complement to their regular mathematics instruction which uses Eureka Math (Great Minds, 2018) the other days of the week. On Navigate Math Wednesdays, students worked for 90 min on their individual Navigate Math courses while the teacher circulated and answered questions. The teacher uses the data from Navigate Math Wednesdays to create small groups to differentiate instruction throughout the week. In addition, students were given an opportunity to study with Navigate Math independently during the week when they completed their other coursework. These students spent approximately 445 total hours on Navigate Math during the research study with an average time per student of 7.8 hr during the 3-month period.

TABLE 5 Case 1 results: Fifth grade students with Navigate Math Wednesdays (n = 57)

	β	SE	t	p	F	df	p	Adj. R^2
NWEA winter MAP score					20.99	(3, 53)	.0000	0.5171
(Intercept)	92.604	17.511	5.29	.000				
Fall MAP math score	0.628	0.123	5.10	.000				
Fall MAP reading score	−0.078	0.103	−0.75	.455				
Competencies gained with the Navigator	0.402	0.200	2.01	.049				

TABLE 6 Results of MANOVA for regression on (a) Operations and Algebraic Thinking and (b) Real and Complex Number Systems

	Wilk's λ	F	df	p
Overall model	0.6902	3.16	2	.020
Original score	0.7710	4.60	1	.018
Competencies gained with the Navigator	0.7913	4.09	1	.027

Over the course of 3 months of implementation with Navigate Math, students demonstrated 488 competencies. For data analysis, linear regression and multiple linear regression models were used to analyze potential relationships between activity stream data in Navigator for Math and NWEA MAP scores, which are assessments designed by NWEA, a research based nonprofit. The MAP assessments are implemented multiple times a year to track student growth and areas of strengths and weakness. A linear regression was constructed with overall Winter NWEA MAP as the dependent variable while controlling for previous performance on math and reading MAP scores. The regression model (Adj. R^2 = 0.5171, F[3,53] = 20.99, $p \leq .0001$) shows a direct positive correlation to competencies mastered in Navigator for Math to overall Winter MAP scores. On average, students who gained more competencies in Navigator for Math had higher overall MAP scores. In addition, after 3 months of interaction with Navigate Math but a relatively small dose (e.g., average of 7.8 hr per student), 70% of students in one class and 50% of students in the other class met the MAP goals that were set by their teachers in the fall MAP testing period (see Table 5).

4.2 | Case 2: Remedial ninth grade math

In Case 2, the teacher used the Learning Navigator with two full periods of remedial math where students were 3–5 grade levels behind in math. The ninth grade students focused on Navigate Math topics and concepts within Operations and Algebraic Thinking and the Real and Complex Number systems. These areas were determined to be core areas for improvement by the administrators and teachers prior to the school year. Based on this decision, the students focused their studies on these topics, and they did not study Geometry and Statistics/Probability.

This teacher used Navigate Math in two ways: to support and reinforce current grade level material in selected topics, and to foster progress on selected math concepts. Three days a week, the classes began with more traditional lectures based on the Discovery Education curriculum followed by students' interaction with activities in Navigate Math to reinforce learning and to fill fundamental gap through interaction with the same Common Core material in multiple ways. Two days a week during small group time, the teacher and co-teacher worked with student groups on Navigate Math while others worked independently. In Case 2, each student on average spent 17.7 hr on Navigate Math during the research study.

A multiple linear regression indicated a statistically significant positive correlation between competencies gained with the Navigator and NWEA Winter MAP scores in the areas of Operations and Algebraic Thinking and The Real and Complex Number Systems. The model was jointly significant (Wilks λ = 0.6902, F = 3.16, p = .0199, see Table 6) and the covariate corresponding to competencies gained on Navigate Math was jointly significant across dependent variables (F = 4.09, p = .027).

Table 7 provides the full results of the multiple linear regressions. The competencies earned with Navigate Math was a strong postive predictor of both the Operations and Algebraic Thinking NWEA Map Score (β= 0.607, t= 2.60, p= .014) as well as the Real and Complex Number Systems NWEA Map Score (β= 0.390, t= 2.22, p= .034). No statistical relationship was found between competencies gained with the Navigator and the scores for (a) Geometry and (b) Statistics and Probability. Both of these topics were not studied with Navigate Math.

5 | DISCUSSION AND CONCLUSIONS

This paper presented a conceptual model and case study research on the simultaneous design of a technology-rich data backbone system, the Learning Navigator, with the design of a pedagogical approach, Navigated Learning. The team combined fundamental research and expertise in the learning sciences, data science, and artificial intelligence to design and implement a pedagogical approach that complements traditional instruction to enhance a classroom teacher's ability to differentiate learning within heterogeneous classrooms. The two cases illustrated two very different uses of Navigate Math in classrooms, including one model to complement traditional fifth grade mathematics instruction and a second model to provide additional and varied support for struggling ninth grade students on concepts of particular importance to the classroom teacher and school administrators. In both cases, students utilized Navigate Math in relatively small doses and to meet specific goals established by the classroom teacher. In neither case did Navigate Math come close to replacing traditional

TABLE 7 Multiple linear regression coefficients and statistics for (a) Operations and Algebraic Thinking and (b) Real and Complex Number Systems

	β	*SE*	*t*	*p*	*F*	*df*	*p*	R^2
Operations and Algebraic Thinking NWEA map score					4.42	(3, 35)	.020	0.22
(Intercept)	113.75	54.66	2.09	.045				
Original score	−0.557	0.256	−2.17	.038				
Competencies earned with the Navigator	0.607	0.233	2.60	.014				
Real and Complex Number Systems NWEA map score					5.12	(3, 35)	.011	0.24
(Intercept)	116.07	41.02	2.83	.008				
Original score	−0.555	0.193	−2.87	.007				
Competencies earned with the Navigator	0.390	0.176	2.22	.034				

instruction or replacing the classroom teacher. Instead, the amount of instructional time spent on Mathematics in both cases was identical to previous years and the teacher remained in full control of classroom instruction for all students. Yet in both cases, the research results demonstrate significant positive correlations by students in targeted areas of Mathematics with even a relatively small dose of the intervention materials that were tailored to individual student or small group instructional needs and goals.

Teachers and administrators were pleased with several aspects of the Navigate Math implementation. In both cases, teachers and administrators were encouraged to design their own way to customize the implementation of Navigated Learning to meet their needs. In Case 1, over half the fifth grade students met their stated MAP goals, which was an important milestone for students, the classroom teacher and the school administrators. The teachers reported that this was the best their students have done on MAP testing. In Case 2, the ninth grade students obtained a positive correlation between competencies in Navigator Math and Winter MAP scores in the topics where students worked with Navigate Math (e.g., Operations, Algebraic Thinking, Real and Complex Number Systems). As mentioned earlier, there was no correlation between competencies in Navigator Math and Winter MAP scores on the other topics that were not studied using Navigator Math, such as Geometry. These ninth grade student results were particularly encouraging to the classroom teacher and school administrators as they provided promising early results for students who had not had a great deal of prior success in these mathematics topics.

Despite the technology-rich system and data-rich backbone, a central dimension of the Navigated Learning pedagogical approach is that technology is not seen as a comprehensive replacement for teacher-guided classroom instruction. Instead, we see the fourth component of Navigated Learning, Facilitate, as the place where the dynamic between the technical and human sides of design were most evident. In Facilitate, each teacher's goals and pedagogical norms were not just respected but championed. Navigated Learning is different from other approaches, such as Summit Learning, because in Navigated Learning, the role of the teacher as the instructor is crucial. The Navigator system is designed to recognize and, ideally, enhance teaching and learning through more information and the capacity for more detailed decision-making so that each teacher can expand their ability to differentiate instruction for each of their students. The system did not dictate one approach or use of the tools; instead, the teacher and students were continuously encouraged to use the resources in whatever manner and amount they believed helped them realize their goals.

We have begun to explore wide applications of the Navigator system and the Navigated Learning approach to test its viability. For example, in rural India, we are currently testing the implementation of Navigated Learning within classrooms that have very limited access to technology, such as one mobile phone per classroom. We are also conducting studies of the use of Navigated Learning for skills and concept training for corporations and government organizations.

While we are encouraged by these early results, we recognize there is a great deal of additional research and development needed to optimize the design of these tools and to understand applications across a wide range of students and teachers. We are optimistic about the potential of learning technologies to support classroom teachers in differentiating instruction to serve a variety of learners and purposes, even as we recognize that technology is not a magic bullet to solve the problems of teaching and learning. Learning data backbones provide only increasingly better approximations of what the learner knows and is able to do. Nevertheless, we remain optimistic about what affordances technologies can provide for teaching and learning. As discussed here, when both the technical side and the human side of emerging digital technologies are considered, learning technologies can enhance the teacher's ability to provide differentiated resources, tailored feedback, customized suggestions and detailed transparency about what the learner knows and is able to do. We look forward to additional research and development to optimize the successive approximations of the learner available to teachers and learners and to understand the dynamic between humans and technology that allow the differentiation of learning for all learners and goals.

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