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Impact on mathematics self-beliefs from a mastery-based mathematics software

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ABSTRACT

Self-beliefs are important determinants of student choice and success (Wigfield & Eccles, 2000) and are informed by student educational experiences, such as prior success with a task (Bandura, 1986). The potential for Computer-Based Interventions as self-belief-supporting learning environments is examined in this study, focusing on the mathematics software, Spatial Temporal (ST) Math. ST Math includes elements theorized to support student self-beliefs, including informative feedback and a self-pacing structure. Using a randomized control trial, we find that students who play ST Math have higher mathematics self-beliefs than their control counterparts, and that ST Math operates through self-beliefs to positively influence achievement. ST Math's impact on student self-beliefs is strongest for those students who had lower mathematics achievement scores.

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Mathematics achievement during the compulsory schooling years is a strong predictor of later labor-market success (Murnane, Willett, & Levy, 1995; National Academies of Sciences, Engineering, and Medicine, 2016; NSB, 2015; Ritchie & Bates, 2013). However, children from low-income communities and ethnically and linguistically minority groups suffer from significantly lower levels of mathematics achievement than children from higher-income and non-minority communities (National Center for Education Statistics, 2017). This is troubling because persistent difficulty with mathematics is one of the strongest predictors of dropping out of college and failure to enter college (Duncan & Magnuson, 2011).

Interventions, especially those in the family of computer-based instruction, have gained popularity as a method to improve student mathematics skills (e.g., Cheung & Slavin, 2013; Chodura, Kuhn, & Holling, 2015; Higgins, Crawford, & Silvestri, 2016; Li & Ma, 2010; Ok & Bryant, 2016). To maximize effects, measuring success of these programs on test scores may not be enough—researchers must understand the mechanisms through which these programs work. Given the engaging and often personalized nature of computer-based interventions (CBIs) (e.g., Kim, 2012; Walkington & Bernacki, 2019), student motivation presents a promising mechanism through which CBIs may advance student achievement. In particular, a student's self-beliefs—or their judgment that they will be able "to organize and execute courses of action required to attain designated types of performances" (Bandura, 1986, p. 391)—are of interest to researchers and practitioners because of the strong ties between self-beliefs and choice of activities, effort, and persistence (Zimmerman, 2000). In other words, students who believe they can accomplish a task are more likely to invest time and effort in working toward this accomplishment, even in the face

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of difficulty. In the domain of mathematics, these self-beliefs have been found to be strong predictors of academic achievement (e.g., Fast et al., 2010; Multon, Brown, & Lent, 1991; Pajares & Miller, 1994). Within the current paper, we explore the application of features common to some CBIs as a method to improve student self-beliefs, and through self-beliefs, achievement in mathematics. We use a randomized experimental study of the elementary mathematics software, Spatial Temporal (ST) Math, as a test case for our hypotheses.

Mathematics Self-Beliefs

Prior academic achievement is a powerful predictor of subsequent academic performance (Hemmings, Grootenboer, & Kay, 2011). However, motivation—the initiation and sustainment of an activity (Schunk, Pintrich, & Meece, 2008)—is also responsible for differences in outcomes that aren't explained by academic ability alone. For example, motivation, including self-beliefs, can explain individual differences in choice behaviors, engagement, and persistence (Wang, Eccles, & Kenny, 2013; Wigfield & Eccles, 2000). There is robust empirical support for the role of student motivation in academic achievement in the domain of mathematics (e.g., Keys, Conley, Duncan, & Domina, 2012; Linnenbrink, 2005; Shell, Murphy & Bruning, 1989). Thus, efforts to improve not only the content of curriculum and the quality of instruction but also student motivation are useful in the overall goal of improving students' mathematics learning and achievement.

Within the research literature on motivation, one factor has particular value in raising academic achievement—the child's *expectancy* to perform well (Wigfield, 1994; Wigfield & Eccles, 2002). Expectancy is defined as a self-prediction of how well one will do on an upcoming task (Wigfield & Eccles, 2000). Because expectancy is empirically inseparable from other competence beliefs, especially among elementary-aged children (Wigfield, 1994), we rely upon the broader term, *self-beliefs*, to represent concepts such as self-efficacy (Bandura, 1997), expectancy (Wigfield, 1994; Wigfield & Eccles, 2000), and self-concept (Marsh, 1993). Care is taken to apply the respective term used by researchers in discussing past work.

The relationship between self-beliefs and achievement has been discussed in the education research literature for over four decades (e.g., Bandura, 1977). This relationship is robust: a meta-analysis of 39 studies revealed a positive and statistically significant relationship between self-efficacy beliefs and academic performance and persistence across a wide range of subjects, experimental designs, and methods (Multon, Brown, & Lent, 1991). Similarly, a more recent meta-analysis of 51 studies found a consistent moderate positive relationship between academic self-efficacy and academic performance (Honicke & Broadbent, 2016). Research points to mechanisms through which self-beliefs influence achievement and persistence; specifically, self-efficacy influences task choice and strategies, goal orientations, effort, perseverance, and resilience *(*Bandura, 1997; Honicke & Broadbent, 2016; Schunk, 1995). For example, one study showed that students with high self-efficacy for math problem-solving tended to monitor their performance and persist longer on problem-solving tasks than did students with lower levels of self-efficacy; this persistence led to greater math learning (Bouffard-Bouchard, Parent, & Larivee, 1991).

ST Math

The ST Math program was created by MIND Research Institute (MIND) to teach mathematical reasoning to elementary-aged children through game-like software aligned with state math content standards. ST Math software allows children to interact with spatial temporal problems through individualized instruction based on each student's pace of learning. Each puzzle within ST Math is based on a simple goal: get Jiji the Penguin out of the frame. In Figure 1, students must place a balloon basket appropriately so that the tire feature on which Jiji stands will unroll

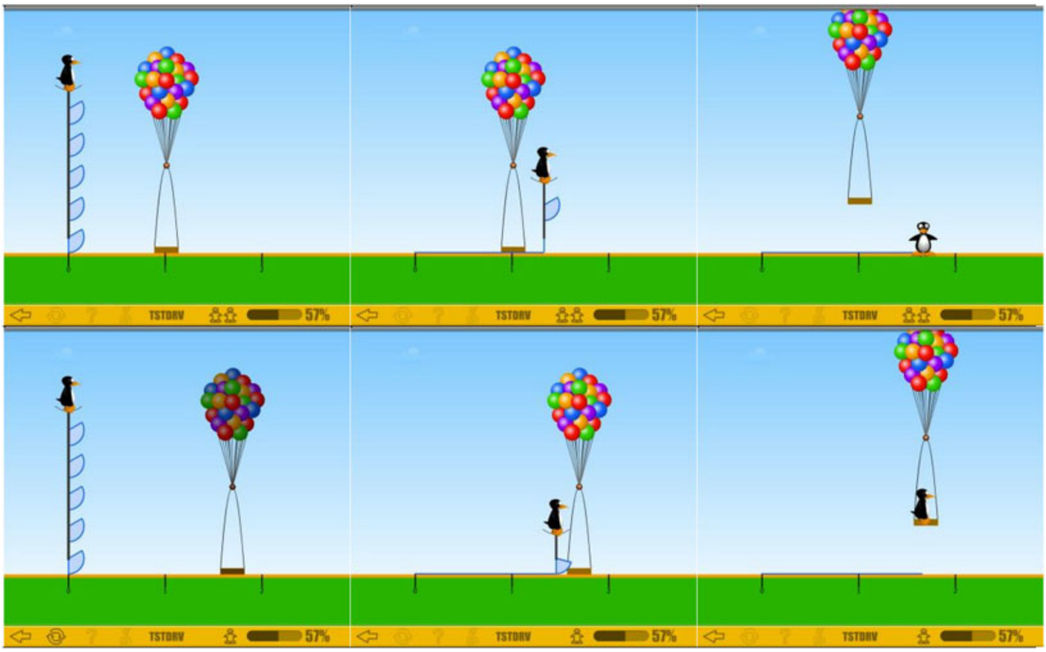

Figure 1. This ST Math game covers fraction addition for third graders. The student must place the balloon basket where JiJi the Penguin will end up when the tires unroll. Here, the students must realize each tire section is 1/3. In the top row, the student places the basket too close, and when the tires unroll, Jiji is left on the ground, as the basket takes off without them. In the bottom row, the student places the basket correctly (with a small margin of error allowed) and Jiji is lifted off with the basket.

and place Jiji on the basket so that Jiji can be lifted out of frame. Within ST Math, problems are represented as games with increasing levels of difficulty. The first level of each ST Math game generally allows for immediate success for students. When a student "beats" a level, they are rewarded with a slightly more difficult level focusing on more challenging aspects of the same content. The process of moving forward after completing a level allows for gradual scaffolding from simpler to more complex mathematics. In the higher-level games, children interact with more difficult math principles, larger quantities, and multistep problems. The program is designed to be integrated into the curriculum through coordination between teacher-led instruction and software design to scaffold each child's learning at the appropriate pace and level of difficulty. Previous research has shown small positive effects of ST Math on mathematics achievement, measured as broad state standardized tests (Rutherford et al., 2014). MIND and teacher-users of ST Math note anecdotally that ST Math is motivating for students (Peddycord-Liu et al., 2019). Below, we discuss antecedents of self-beliefs and explore how features of the games may act to increase this type of motivation.

Antecedents of Self-Beliefs and the context of ST Math

Bandura (1977, 1986, 1997) asserted that self-efficacy is influenced by four primary sources of information: 1) firsthand experience with a specific task; 2) vicarious learning through watching someone else complete a specific task; 3) verbal persuasion related to the task, including encouragement or discouragement; and 4) emotional arousal (either good or bad) when completing the task or watching the task being completed. ST Math may work to support math self-efficacy or expectancy by influencing a number of these factors.

The four sources are related; interviews with students suggest that they develop heuristics to combine information from the four sources and define their self-efficacy beliefs (Usher, 2009).

For example, first-hand experience can combine with a form of verbal persuasion in the form of feedback. Research has confirmed that providing students with process goals to guide their first-hand experiences, along with feedback on their process, can lead to increases in student self-efficacy (Lai & Hwang, 2016; Schunk, 1995; Schunk & Lilly, 1984). In Lai and Hwang (2016), fourth grade students in an experimental group were asked to set learning goals before engaging in learning activities, and were given feedback by their teachers after the learning activity was completed. The goal-setting/feedback group reported statistically significantly higher self-efficacy than did the control. Schunk and Shwartz (1993a; 1993b) found similar benefits of goal setting, but found that feedback benefited student self-efficacy across groups.

Frequent and informative feedback is a desired feature for successful digital learning games (Qian & Clark, 2016). ST Math offers students frequent feedback both on the result of actions and on process: students are immediately shown whether they got the correct answer, and the method for finding the correct answer is illustrated after each trial with animations. For example, in Figure 1, the animation illustrates *why* the answer in the top row is incorrect, showing that when added together end-to-end, five thirds are greater than one. This visual unpacking of each math problem is consistent across all the games within ST Math; students are shown the visually-represented consequences of their choice in the context of the mathematics within the puzzle.

A sense of general agency has also been positively linked to self-efficacy beliefs: individuals who believe that they have control over their actions tend to develop higher levels of self-efficacy (Schunk, 1982; Weiner, 1985). Self-efficacy is also enhanced when students believe they are performing well or improving at a task (Arslan, 2012; Williams & Williams, 2010). If individuals believe they can perform better by working harder at the task, then even slow progress or failures will not lower self-efficacy (Schunk, 1995). CBIs, like ST Math, can provide adaptive learning environments wherein content is matched to a student's particular capabilities. ST Math's highly scaffolded approach allows students to experience success on lower, easier levels of the game. The levels increase in difficulty by small increments, providing many more opportunities for success along the way. Although students must follow the game's predetermined playing order, their pace through the games is not dictated by the teacher or the performance of their peers, but by each student's personal record of incremental success.

Schunk and Miller (2002) noted that students need opportunities to persist through failures in their academic career if they are to learn that hard work can lead to better outcomes, a self-efficacy protecting belief. This persistence through failure is a feature of mastery-focused classrooms in which mistakes are viewed as a part of learning (Ames & Archer, 1988; Meece, Anderman, & Anderman, 2006). Standard math curricula do not provide students with motivating opportunities to view mistakes as building blocks that ultimately lead to academic success. Rather, mistakes are often viewed as conclusive failures with long-lasting consequences (Boaler, 2013, 2016). This type of environment dampens student motivation and leads to decreased persistence (e.g., Dickhäuser, Buch, & Dickhäuser, 2011; Haimovitz & Dweck, 2017; Miller & Blumenfeld, 1993). Conversely, the ST Math curriculum allows students to view obstacles and mistakes as productive building blocks toward significant learning. ST Math creates opportunities for students to fail frequently as they grapple with math problems within the software while the game provides support to push through failures. Students can also receive help through teachers who have tools to monitor student individual progress—teachers receive instruction on how best to guide students whenever they are "stuck." The increments of learning provide opportunities to fail in a safe environment, where multiple attempts at success following setbacks are not overwhelming. This view toward failure is part of the MIND theory of change and is noted by teachers as a valuable aspect of ST Math (Peddycord-Liu et al., 2019).

Recently, interventions to directly influence motivation, including self-beliefs, by targeting the above factors have met with success in both improving motivation and achievement (e.g., Bartsch, Case, & Meerman, 2012; Cleary, Velardi, & Schnaidman, 2017). The greatest self-belief improvements were generally found when interventions emphasized praise or feedback (O'Mara, Marsh, Craven, & Debus, 2006). For example, Luzzo, Hasper, Albert, Bibby, and Martinelli (1999) assigned undergraduates to one of four conditions: (1) complete a relatively simple number task and receive feedback that they succeeded at the task (first-hand experience and verbal persuasion), (2) watch a video of two graduates talking about their math and science careers (vicarious learning), (3) both complete the number task and watch the video, or (4) do nothing. Students who completed the number task (either alone or in combination with vicarious learning) showed greater improvements in math self-efficacy. Further, interventions targeting initially disadvantaged participants (e.g., those with lower performance or motivation) were also more effective than interventions aiming to maintain moderate or higher levels of self-beliefs (e.g., O'Mara et al., 2006; Pareto, Arvemo, Dahl, Haake, & Gulz, 2011).

There have also been general interventions that indirectly improve self-beliefs, although these indirect interventions have an overall lower effect size for improving self-beliefs compared to direct interventions (O'Mara et al., 2006). In the realm of CBIs, two studies may be particularly informative. Ritzhaupt, Higgins, and Allred (2011) found correlational support for links between middle school student play of an educational math game and improvements in student attitudes toward math and their math self-efficacy, although students did not improve in their mathematics achievement. Pareto and colleagues (2011) conducted a randomized study of a nine-week teachable-agent arithmetic game and found improvements in both mathematics self-efficacy and achievement; however, self-efficacy questions were measured using specific problems taught within the agent—a fairly narrow measure of mathematics beliefs with respect to content. More experimental work is needed to further explicate the causal link between mathematics CBIs and improvements in self-beliefs, especially focusing on games that have embedded mechanisms theorized to support positive student self-beliefs, such as those within ST Math.

The current study

ST Math provides students with incremental process goals, provides feedback on each student attempt, and allows students to self-pace through increasingly difficult material. MIND's theory of change posits that students will be driven to improve upon their personal best—a feature common to games-based learning (Ke & Abras, 2013)—and persist through transient failures that allow them to repeatedly experience success during mathematics learning. All these factors are associated with mastery-focused learning environments (Ames & Archer, 1988; Brookhart, 1997), and in turn with increased self-beliefs. The present study explores the relationship between ST Math, self-beliefs, and achievement within the context of a randomized trial. The effect of ST Math on achievement was presented previously in Rutherford et al. (2014); however, the motivation results reported herein have not been previously published. In the current study, we ask (1) Does ST Math positively influence student mathematics self-beliefs? (2) Does influence on student mathematics self-beliefs partially or fully explain ST Math's effect on mathematics achievement? (3) Does ST Math's influence on student self-beliefs differ depending on student's initial mathematics performance level? Although these questions are specific to ST Math, we view the results herein as a case study of a CBI with motivation-supportive features. As such, we expect our results can be applied beyond the specifics of this particular software.

Method

Participants and procedures

Data were collected as part of an IES-funded project to study the impact of ST Math on mathematics achievement and cognitive and motivational outcomes. The project included all second through fifth grade students at 52 Southern California schools, each with high percentages of English Language Learners and students qualifying for free or reduced lunch.

Participating schools were randomly assigned at the school level to either A schools—those who would initially implement ST Math in 2nd and 3rd grades, or B schools—those who would initially implement ST Math in 4th and 5th grades. In this way, students receiving ST Math could be compared to their same-grade peers in other schools who were not receiving ST Math in that grade-level, with each school serving as both treatment and control, depending on grade. Thirty-four schools (Cohort 1) began implementation in the 2008-2009 school year and 18 schools (Cohort 2) began implementation in the 2009-2010 school year; each Cohort was divided between A and B schools. In subsequent years, students who received ST Math continued receiving ST Math, at least through 5th grade. Treatment grades implemented ST Math as supplemental to their normal mathematics curriculum. Control grades implemented business as usual models for mathematics instruction. Further details on the randomization and treatment assignment are available in Rutherford et al. (2014). In a survey as part of the project, treatment teachers indicated that time for ST Math largely came from non-mathematics subjects, such as Language Arts, Science, and Social Studies (Kunze & Rutherford, 2018). The present study concentrates on the 18 Cohort 2 schools, who were followed with individual student testing in 2011.

All students in grades two, three, and five within the 18 schools were sent consent forms asking for parent permission to engage in individual testing. Teachers were incentivized to obtain completed consent packets with reams of paper awarded to teachers with 80% of their class packets returned. Teachers were blind to parent decision—packets were counted as returned whether parents granted consent or not. The regional school district handled consent procedures and provided the research team with rosters of all students with consent. Although the exact response rate is unknown, the regional district provided an estimated response rate of approximately 60%. The present study is limited to fifth graders. Because of the design of the study and accountability testing policies in place, only fifth grade students had data on pre-ST Math test scores.

In the spring of 2011, research teams of three to five trained undergraduate and graduate students spent two days in each school testing students for approximately three hours each day. Students were randomly selected for testing, stratified by teacher, from among those with consent. Teams were able to test between six and 12 students at a time using individual netbook computers set up in a school library or empty classroom. At prearranged times, students were escorted from class as a group to the testing room. Written assent was obtained, and students completed the netbook assessments with technical assistance, when requested, from the researchers.

For this study, 360 fifth grade students completed the self-belief measures. This is 22% of the 1,649 fifth graders within the study schools in 2011. The analysis is limited to the 331 students who also had demographic data and achievement data from the concurrent year (2011) and from the year before the intervention (2009). The only statistically significant difference between the retained analysis sample and the excluded students was that the analysis sample had slightly more students eligible for free/reduced priced lunch. The sample did differ from other students in the same schools who did not complete the self-belief measures: both treatment and control students among those surveyed has higher state achievement scores than those not surveyed in each year from 2009 to 2011. There were no treatment/control differences in achievement at pretest. The only demographic difference between treatment and control students was in the representation of English Language Learners (ELL)—more control students had a designated ELL status during fifth grade (56% vs. 42%). Descriptive statistics for the study sample are provided in Table 1.

Table 1. Descriptive statistics and demographics of sample, separately by treatment and control.

	Control		Treatment		
	Mean (SD)	Range	Mean (SD)	Range	*p* of diff
Math CST 2009	370.80 (79.23)	224.00–600.00	375.06 (74.00)	193.00–600.00	.614
Math CST 2010	370.42 (69.47)	212.00–538.00	392.05 (69.45)	240.00–600.00	.005
Math CST 2011	380.91 (87.47)	183.00–600.00	399.58 (89.78)	232.00–600.00	.056
Math Self-Beliefs	5.04 (1.31)	1.60–7.00	5.45 (1.14)	1.80–7.00	.002
	Percent		Percent		
Male	53%		53%		.970
Eng. Lang. Learner	56%		42%		.011
Free/Reduced Lunch	82%		87%		.195
White	6%		6%		.954
Asian	6%		3%		.252
Hispanic	87%		88%		.664
Other Race/Ethnicity	1%		2%		.542
N	151		180		

Note. Demographics as reported in 2011, during fifth grade. Math CST is the Mathematics California Standards Test. Possible range on CSTs was 150–600. Possible range on self-beliefs scale was 1–7.

Measures

Self-belief measures

Expectancy items from Eccles et al. (1993) expectancy–value scales were administered to sampled students. The validity and reliability of these scales have been established in previous educational research, including within the context of mathematics (Wigfield & Eccles, 2000). Although these scales are commonly used to measure expectancy, many of the items align more closely with self-concept (e.g., "How good at math are you?") and so are referred to within this study as self-beliefs (see Eklöf, 2007). The items were administered individually via netbook computers. The survey was designed as an experiment in E-prime 2.0. Students were first presented with a narration instructing them that the survey was not a test, there were no right or wrong answers, and researchers were only interested in their opinions. Students then completed two practice questions focusing on the topic of spelling before completing the mathematics motivation measures. Each question was presented both visually and narrated to students; options were provided as a 7-point Likert-type scale (Figure 2). Five self-beliefs items were averaged into a self-beliefs scale (alpha=.87).

Standardized tests

All California 2nd through 5th graders, including our study participants, took the California Standards Test (CST) in the spring of each year through 2013 when the state transitioned to a new testing system. The math portion of the CST measured grade-level math material aligned to the California content standards. The alpha reliabilities for 2nd and 3rd grade math CSTs were reported in 2013 as .93 and .94 respectively (Educational Testing Service, 2014). CSTs are measured on a scale of 150-600; a scale score of 350 points is the state-specified proficiency marker. School districts provided CST scores along with demographic information for study participants.

Analysis

Two-level random intercepts multilevel models were estimated to account for nesting of students within schools. As an initial step, zero-order correlations were calculated and the intraclass

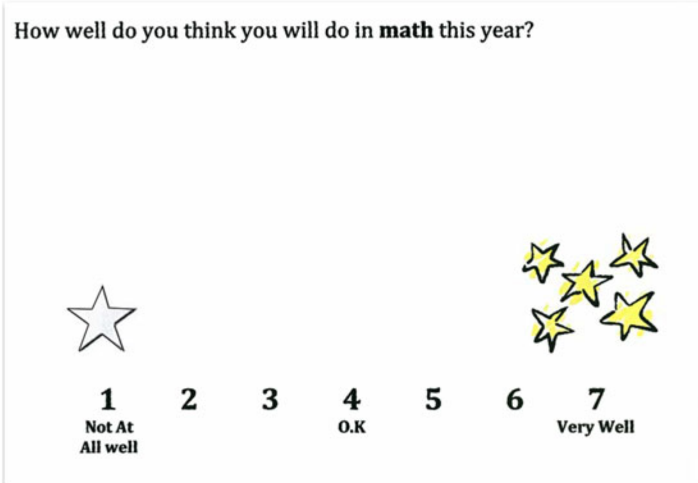

Figure 2. A question assessing student expectancy for math success. Trained research assistants read this and other similar questions aloud while students looked at the pictures. Students indicated their answer by giving the corresponding number.

Table 2. Zero-order correlations between variables.

$N = 331$	ST Math	Self-Beliefs	Math 2009	Math 2010
Self-Beliefs	.166**	1		
Math 2009	.028	.461***	1	
Math 2010	.154**	.470***	.703***	1
Math 2011	.105†	.493***	.648***	.737***

Note. †$p < .10$, *$p < .05$, **$p < .01$, ***$p < .001$.

correlations (ICCs) between outcomes and school were examined. Schools were chosen as the nesting variable because treatment was assigned at the school level and because some teachers only had one student who contributed data. The mean number of students contributed by school was 18.39 (SD: 6.34, range 6-30).

For question 1, we regressed self-beliefs on ST Math treatment, 2009 math scores, and demographic covariates (gender, ELL status, eligibility for the free/reduced lunch program). For question 2, paths were estimated from self-belief scale to 2011 math score (path A), from treatment to math scores without the self-beliefs mediator (path C), and from treatment to math scores including self-beliefs (paths C' and B) (Baron & Kenny, 1986). To test the statistical significance of the indirect pathway, bootstrapped tests of mediation (5,000 iterations) were conducted with the ml_mediation algorithm within Stata 13 (StataCorp, 2015; Krull & MacKinnon, 2001). For question 3, we created an interaction term multiplying treatment status and 2009 (pretest) math score. This term was added to the question 1 model.

Results

Zero-order correlations are presented in Table 2. Treatment is positively correlated with mathematics self-beliefs and with mathematics test scores in 2010—the test administered after one year of treatment. Self-beliefs are moderately and positively correlated with test scores from all three years; test scores correlate year-to-year at or above .65. As students are nested within schools, we examined the percentage of variance at the school level for self-beliefs and for 2011 math test scores. Three percent of the variance in self-beliefs and 13% of the variance in test scores was between schools. Below, multilevel regression results are provided for each of our research questions.

Table 3. Results of regression analyses for questions 1 and 2.

	Self-Beliefs		Math 2011		Math 2011	
	B (SE)	*p*-value	B (SE)	*p*-value	B (SE)	*p*-value
Treatment (ST Math)	0.455 (0.153)	.003	9.466 (17.480)	.588	1.143 (16.562)	.945
Self-Beliefs					17.209 (3.017)	<.001
Math 2009	0.009 (0.001)	<.001	0.735 (0.049)	<.001	0.583 (0.054)	<.001
Male	0.140 (0.119)	.236	−2.890 (6.681)	.665	−5.749 (6.399)	.369
Eng. Lang. Learner	0.430 (0.135)	.001	−28.209 (7.761)	<.001	−35.492 (7.518)	<.001
Free/Reduced Lunch	−0.064 (0.178)	.719	5.816 (10.272)	.571	7.240 (9.809)	.460
White	−0.095 (0.268)	.724	−33.093 (15.147)	.029	−32.284 (14.463)	.026
Asian	−0.160 (0.296)	.589	22.868 (16.669)	.170	25.840 (15.925)	.105
Other Race/Ethnicity	0.243 (0.445)	.585	15.302 (25.012)	.541	11.389 (23.893)	.634
Constant	1.559 (0.402)	<.001	126.122 (25.264)	<.001	100.294 (24.476)	<.001
Random Parameters	B (SE)	95% CI	B (SE)	95% CI	B (SE)	95% CI
Between	0.199 (0.089)	0.083 − 0.478	33.938 (7.430)	22.096 − 52.126	31.959 (7.082)	20.700 − 49.341
Within	1.055 (0.043)	0.975 − 1.141	58.748 (2.379)	54.266 − 63.601	56.100 (2.276)	51.811 − 60.743
N	331		331		331	

Note. Results from random intercepts with students nested within schools ($N = 18$). Demographics as reported in 2011 (5th grade). Math scores are California Standards Tests. Math 2009 is prior to treatment. Math 2011 is after two years of treatment.

Question 1: Does ST math positively influence student mathematics self-beliefs?

Multilevel regression results for Question 1 are presented in the first column of Table 3. Taken together, included variables explain 27% of the variance in student self-beliefs. Treatment emerges as a statistically significant predictor. Standardized betas are calculated using the formula (B*SDx)/SDy. Among this sample, treatment students have self-beliefs over a third of a standard deviation higher than those of control students ($\beta = 0.37$). Comparatively, prior mathematics score is related to self-beliefs such that each standard deviation increase in math score is associated with a 0.54 standard deviation increase in self-beliefs, a result consistent with prior literature (Chen, 2003; Huang, 2011, Marsh et al., 2015). Among the demographic variables, only ELL status emerged as a statistically significant predictor of self-beliefs; on average, ELL students' self-beliefs were 0.35 of a standard deviation higher than non-ELL students. Because of this association, and because ELL students were overrepresented in the control condition, we investigated a treatment-by-ELL interaction; this was not statistically significant ($p = .349$).

Question 2: Does any improvement in student mathematics self-beliefs partially or fully explain ST math's effect on mathematics achievement?

Although we based our mediator question on prior results showing that ST Math has a small total effect on student math scores (Rutherford et al., 2014), we were not able to replicate this effect among the students in our sample. As seen in the middle column of Table 3, the association between treatment and 2011 mathematics CST scores was not statistically significant

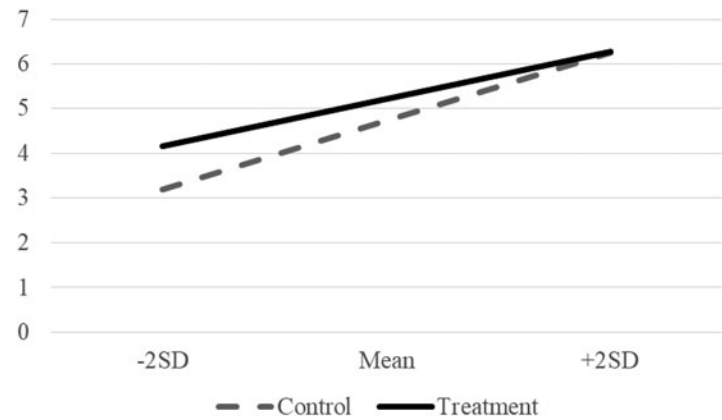

Figure 3. Effect of ST Math on Self-Beliefs Moderated by Prior Achievement. Regression-adjusted unstandardized coefficients graphed at three points separately for treatment and control: the mean of pooled achievement, two standard deviations below the mean, and two standard deviations above.

(p = .588), with a beta value of 0.12. We nevertheless proceeded with our bootstrapped mediation analyses to test the indirect effect of ST Math on test scores through self-beliefs, as indirect effects can still be statistically significant and/or meaningful without the presence of a statistically significant total effect (Hayes, 2009). Although we ran 5,000 iterations for our bootstrapped tests of mediation, 15 iterations could not be estimated; our results are based on 4,985 replications. A statistically significant indirect effect emerged (B = 7.84, p < .001, [CI = 3.60, 12.08]). We calculated a partially standardized indirect effect by dividing the unstandardized coefficient by the SD of our outcome variable as described in Preacher and Kelley (2011), as Hayes (2009) does not recommend completely standardized indirect effects when X is dichotomous. On average, treatment students gain just shy of one-tenth of a standard deviation (β = 0.09) in test score through the positive effect of ST Math on student self-beliefs.

Question 3: Does ST Math's influence on student self-beliefs differ depending on student's initial mathematics performance level?

Given the effect that ST Math had on student self-beliefs and research showing that motivation interventions might have stronger effects on lower performing students (e.g., Hulleman, Godes, Hendricks, & Harackiewicz, 2010) we examined initial student mathematics performance as a moderator of the link between ST Math and self-beliefs. Including an interaction term between treatment and prior mathematics score explained an additional 1.43% of the variance in student self-beliefs and resulted in a statistically significant (p < .05) reduction in the deviance statistic. The interaction term (B = 0.003) was also statistically significant (p = .04). Figure 3 illustrates the interaction effect by examining treatment/control differences for those at the mean of prior achievement and two standard deviations above and below. For those two standard deviations below the mean (a score of approximately 220 on the CST), on average, treatment students have self-belief values nearly a point above those in the control group—0.77 of a standard deviation. However, for students two standard deviations above the mean (a score of approximately 526 on the CST), on average, there is very little difference between treatment and control students' self-beliefs—0.03 of a standard deviation.

Discussion

Using data collected from a randomized experimental study, we investigated the effect of a mastery-based mathematics software on students' expectancies for success. Features of the ST Math curriculum include individually-tailored instruction, immediate feedback, and increasing difficulty on content and tasks—collectively thought to enhance student self-beliefs related to mathematics (Ames & Archer, 1988; Schunk, 1995). We found that students who participated in the ST Math intervention had higher self-beliefs than their control counterparts, and that self-beliefs were associated with positive changes in mathematics achievement. We also found that within the treatment group, students with initially low mathematics scores benefited more from the ST Math program, receiving a larger boost to self-beliefs compared to treatment students with initially high mathematics scores.

This paper offers causal evidence that an interactive digital learning environment intended to support mastery experiences and persistence does in fact improve students' mathematics self-beliefs. Prior research on CBIs has provided evidence that such interventions can improve student mathematics achievement (Cheung & Slavin, 2013), with some further evidence that they can also improve motivation (e.g., Pareto et al., 2011; Ritzhaupt et al., 2011). The current study extends this research by noting specific features of CBIs theorized to support positive student self-beliefs, and examining the effect of one CBI on mathematics self-beliefs in a randomized study, allowing for stronger causal claims. Our results support the claims made in Pareto and colleagues (2011) regarding the positive motivational impacts of mathematics CBI, but our results hold for a domain-level measure of mathematics self-beliefs. Improving student self-beliefs in mathematics generally can have payoffs outside of ST Math, as students with higher mathematics self-beliefs are more likely to choose to engage in mathematics tasks (Wigfield & Eccles, 2000) and persist when they encounter challenges (Zimmerman, 2000).

Our findings that ST Math had a stronger effect on self-beliefs for low performing students may be due to the incremental nature of the curriculum within ST Math. Low performers in our study were defined based on their standardized assessment scores, score information that may have been communicated to these students through their parents or teachers. It is very likely that this communication and the feedback they receive on classroom assessments provides these students with few first-hand experiences of success. In contrast, levels within ST Math increase in difficulty very slowly, allowing all students to experience multiple level passes, a signal to students that they are good at some element of the task. This serves as first-hand experience of success with mathematics, which boosts self-beliefs (see Bandura, 1997). Such a focus on meeting students where they are and working toward incremental improvement is a recommendation for mastery-supportive classrooms, also theorized to improve self-efficacy (Ames & Archer, 1988). This reasoning is consistent with other studies of motivational interventions that show stronger effects for those with initially lower levels of motivation or performance (Rosenzweig & Wigfield, 2016).

Taken together, these results have implications for the design and implementation of CBIs. Developers can ensure that CBIs have self-belief-supportive features, such as content leveled to allow for success in a way that informs mastery experiences, and frequent, informative feedback, which can serve as a form of mastery experience and verbal persuasion. These can complement aspects of CBIs that feed other positive sources of self-beliefs, such as vicarious learning and emotional arousal (see Bandura, 1977, 1986, 1997). The former may be best realized through digital collaborative environments or others that allow for peer interaction and observation (e.g., Fokides, 2018); research on the latter indicates that CBIs may serve to reduce anxiety and increase positive emotions (e.g., Ciftci, Karadag, & Akdal, 2014). Further, our finding that the motivational benefits were greatest for lower performers can inform educational implementation of CBIs with motivation-supportive features: educators may wish to provide access to such programs for those struggling in a subject. However, educators may wish to use these programs as supplemental to the typical curriculum unless they have demonstrated positive effects on achievement.

Limitations and future directions

Our study is limited in its focus on one specific CBI, ST Math. However, ST Math has features similar to other CBIs and has been found to have a similar impact on achievement (Pellegrini, Lake, Inns, & Slavin, 2018). The particular features noted herein as supporting self-beliefs are likely applicable to other CBIs. Our study is also limited by the particular study population. Although our sample students were demographically similar to those in the study schools, they represent fewer than 25% of the schools' fifth grade students, and study students had higher achievement scores than their peers. Given the greater effect of ST Math on self-beliefs of lower-achieving students, our sample limitations may serve to underestimate our effect. Finally, we tested ST Math as a holistic intervention to improve student mathematics self-beliefs. We were unable to investigate which specific elements of the software were beneficial toward increasing self-beliefs. Future work is planned using trace data and experience sampling methods (see Hektner, Schmidt, & Csikszentmihalyi, 2007) to understand student motivational experiences as they play ST Math and how specific software elements may relate to changes in student motivation. This future work can also update conclusions regarding the motivating nature of CBI. As the data from the current study were collected in 2011, there may have been novelty effects from CBI that are no longer present within the modern (and future) classroom.

Conclusion

Computer-based instruction offers a potential avenue for improving mathematics performance within K-12 education, an important precursor of future college and career success (Duncan & Magnuson, 2011; National Academies of Sciences, Engineering, and Medicine, 2016). Within this study, we find that the CBI ST Math increases mathematics performance through improved student mathematics self-beliefs, and that ST Math's effect on self-beliefs is stronger for those students with initially lower performance. Our results are limited to one CBI; however, the self-belief supportive features within ST Math can be incorporated beyond the current platform. CBIs may provide a relatively easy means for improving self-beliefs: the potential of these interventions is extremely scalable—with a focus on the most efficient ways to enhance student motivation, including self-beliefs, we can ensure that more of our students are able to succeed and persist in the mathematics critical for our nation's success.

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Ethical approval

All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee (include name of committee + reference number) and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Informed consent

Informed consent was obtained from all individual participants included in the study.

Data availability

The authors will share data upon request.

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