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The Math You Need, When You Need It (TMYN): Leveling the Playing Field

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The Math You Need, When You Need It (TMYN): Leveling the Playing Field

Abstract

The Math You Need, When You Need It (TMYN) is a set of online tutorials designed to help students develop and review mathematical skills that are applied in undergraduate geoscience courses. We present results of a three-year study of more than 4000 students in 106 geoscience courses at a variety of post-secondary schools who were assigned TMYN tutorials as supplemental mathematics instruction. Changes in student scores from pre- to post-test suggest that the support provided by programs such as TMYN can begin to reduce the gap between mathematically well-prepared and underprepared students; in essence, TMYN levels the quantitative playing field for all geoscience students. On average, both high- and low-performing students who fully participated in the use of TMYN as a part of their course showed learning gains, although gains were larger for students who performed poorly on the pre-test. Our findings emphasize the conclusion that students who interact with context-specific quantitative problems can potentially improve their mathematical skills, regardless of initial level of mathematical preparation. We suggest that this type of support could generalize to other science courses.

Keywords

Quantitative skills, Geoscience, Online mathematics tutorials

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Cover Page Footnote

Jennifer M. Wenner is a Professor of Geology at the University of Wisconsin Oshkosh and has been active in designing, creating and editing *The Math You Need* since its inception in 2006. Her research currently focuses on teaching quantitative skills in the geosciences and the geochemistry of primitive basalts in the southern Cascades.

Dr. Eric Baer is an Instructor in the Geology Program at Highline College. *The Math You Need* grew out of a program he started at Highline and he is one of the co-creators and editors of the website. He currently researches quantitative literacy in the geosciences and is a member of the leadership team for the SAGE 2YC program.

Introduction

Geoscience courses on post-secondary campuses have long been referred to as “Rocks for Jocks” (e.g., DeLaughter et al. 1998; Gilbert et al. 2012), implying a paucity of “real” science and the quantitative skills that go along with the pursuit of scientific endeavors. Yet, the geosciences encompass the practical application of biology, chemistry, mathematics, and physics (sciences often perceived to be more quantitatively rigorous than geosciences) to the study of the Earth. For more than two decades, the geoscience education community has been pushing for more realistic representations of the quantitative nature of the geosciences in college courses (e.g., Shea 1990; Vacher 1998; Bailey 2000; Lutz and Srogi 2000; Macdonald et al. 2000; Baer et al. 2002; Manduca et al. 2008; Wenner et al. 2009). However, in order to increase the quantitative content of geoscience classes, faculty must be able to address the wide range of students’ mathematical preparation, support students as they apply or transfer mathematics concepts in unfamiliar contexts (Bransford et al. 1999; Fike and Fike 2008; Planty et al. 2008) and find multiple ways to expose students to the power of mathematics as a tool to solve problems in STEM disciplines (Manduca et al. 2008).

The challenge that faces faculty who teach quantitative geoscience courses is to offer adequate opportunities for students to explore the power of mathematics applied to scientific problems and still retain sufficient class time to cover appropriate content. Striking a balance between stimulating mathematically prepared students while assisting those who are underprepared requires creative solutions that encourage students to succeed at the application of mathematics in geoscience contexts (Wenner et al. 2009). The use of web-based resources can afford opportunities for “just-in-time” instruction (Kaseberg 1999; Mueller and Brent 2004) and provide students with context-rich mathematical problems solved at the student’s pace with immediate application in the subsequent class meeting. Providing occasions to apply mathematics to well-conceived contextual examples throughout science courses can also increase students’ motivation and self-efficacy (Perin 2011; Wenner et al. 2011). When students are motivated, supported and effective at addressing quantitative problems, the inequalities in student skills can be reduced so that students find themselves on a more level playing field, able to address the quantitative problems necessary for deep learning in the geosciences.

This paper presents results of multiple successful interventions that employed web-based, asynchronous tutorials to help students review and apply basic quantitative concepts to geological problems in geoscience courses. We present a study of 106 geoscience courses at 37 two- and four-year higher education institutions between Fall 2010 and Fall 2013. The implementations in this study demonstrate effective application of geoscience-based mathematics tutorials in

The Math You Need, When You Need It [TMYN], which provides support to students enrolled in associated courses. The results suggest that effective quantitative support should focus on application of mathematics to relevant STEM disciplinary topics. This disciplinary focus facilitates transfer of pre-existing and learned mathematics to a wide variety of scientific problems and, therefore, increases students' proficiency and success with quantitative science.

The Math You Need, When You Need It

The Math You Need, When You Need It is an online resource¹ that provides quantitative instruction to students enrolled in geoscience courses. Since 2010, TMYN modules have been implemented in a wide variety classes across the geoscience curriculum. Through TMYN, students with disparate mathematical skills learn, review and gain skills, applying basic mathematics to solve quantitative, contextualized geologic problems. Because the geosciences provide a breadth of scientific topics, mathematical skills addressed by TMYN (Table 1) are applied in multiple contexts and can be adapted to a range of geoscience courses. The range of geoscience topics and the modular nature of TMYN allow instructors to choose appropriate quantitative modules (Table 1), to assign them in any order, and to build quantitative activities and assessments around geoscience topics already in a course syllabus.

Table 1
Quantitative modules available through TMYN

<i>Module Name</i>	<i>Web address</i>
Calculating Density	http://serc.carleton.edu/mathyouneed/density/
Graphing (three sub-modules)	http://serc.carleton.edu/mathyouneed/graphing/
• <i>Plotting Points</i>	http://serc.carleton.edu/mathyouneed/graphing/plotting.html
• <i>Constructing a Best Fit Line</i>	http://serc.carleton.edu/mathyouneed/graphing/bestfit.html
• <i>Reading a Point from a Curve</i>	http://serc.carleton.edu/mathyouneed/graphing/interpret.html
Hypsometric Curve	serc.carleton.edu/mathyouneed/hypsometric/
Rates	http://serc.carleton.edu/mathyouneed/rates/
Rearranging equations	http://serc.carleton.edu/mathyouneed/equations/
Slope and topographic maps (two sub-modules)	http://serc.carleton.edu/mathyouneed/slope/
• <i>Calculating Slope from a Topographic Map</i>	http://serc.carleton.edu/mathyouneed/slope/slopes.html
• <i>Constructing a Topographic Profile</i>	http://serc.carleton.edu/mathyouneed/slope/topoprofile.html
Trigonometry	http://serc.carleton.edu/mathyouneed/trigonometry/
Unit Conversions	http://serc.carleton.edu/mathyouneed/units/

¹<http://serc.carleton.edu/mathyouneed/index.html> (last accessed June 1, 2015)

Student-Oriented Modules

TMYN modules are open-access, student-centered, web-based tutorials designed to support self-paced, “just-in-time” student learning (e.g., Kaseberg 1999; Mueller and Brent 2004). Each module includes three student-oriented pages: (1) an introduction to the quantitative concept, (2) worked practice problems, and (3) a culminating post-module quiz.

Pages devoted to introducing the quantitative concept are steeped in online/multimedia theory (e.g., Mayer 2001) and mathematical pedagogies (e.g., Harel 1998; Kaseberg 1999; Mueller and Brent 2004). Each page addresses motivation for learning the concept, introduces a problem-solving algorithm for approaching geoscience problems with similar mathematical underpinnings (including steps that require assessment and evaluation), and walks students through using the “rules” to solve a preliminary contextual problem (Fig. 1). This initial exposure to a specific mathematical concept and related geoscience topics is the first opportunity for students to discover, relearn, or review the quantitative skills needed in their geoscience courses. Providing and supporting the use of an algorithm promotes struggling students’ success, which can increase confidence and self-efficacy when solving quantitative problems (Wigfield and Eccles 2000; Wenner et al. 2011). In addition to the mechanics behind the mathematics, introductory pages are also designed to support long-term learning by connecting contextual geoscience knowledge with conceptual mathematics.

Contextual geoscience application and transfer of mathematical concepts are underscored on the second student-oriented page – the practice problems page. Here, students engage with a page of contextualized practice problems, solved using the provided algorithm (Fig. 1). Drawing on many sub-disciplines within the geosciences, each practice-problems page offers at least three distinct contextual examples, promoting application of math concepts among applications. The practice problems provide students with the opportunity to immediately apply the mathematical concept they learned on the introductory page to a new context; the design of these problems draws on the successful mathematical just-in-time approach to problem solving (Kaseberg 1999; Mueller and Brent 2004) and the necessity principle—that students are better poised for learning when there is an immediate application (Harel 1998, 2000). The geosciences are rich in examples of basic quantitative skills and provide a breadth of scientific contexts; instructors often revisit mathematical concepts multiple times in the same course and TMYN facilitates connections among topics. Repeated exposure to mathematical concepts in multiple contexts has been shown to increase long-term retention (Kenyon 2000; Stevens 2000; Steen 2004), boost student motivation (Wigfield and Eccles 2000; Barkley 2010) and improve transfer of learning (e.g., Salomon and Perkins 1989; Bransford et al. 1999).

Figure 1. REARRANGING EQUATIONS: an example module

Equations are widely used in geoscience (as well as other STEM disciplines); from calculating rates of plate motion or groundwater flow to complex calculations of isostasy. Students often struggle with this relatively basic mathematical concept because it involves algebra and unfamiliar variables important in the Earth.

Introduction Page (<http://serc.carleton.edu/mathyouneed/equations/index.html>)

The Rearranging Equations module begins by addressing students' fear of equations and explaining that equations are important tools for understanding the natural world.

How do I isolate x (or P or T...) in a formula? Rearranging equations to solve for a given variable

Equations as important geological tools

Sometimes, it may seem like your geoscience instructor is speaking another language when he/she talks about equations or formulae. Especially if he/she expects you to "manipulate" or rearrange them! But, equations can provide powerful tools for describing the natural world. In the geosciences, we can describe the behavior of many natural phenomena by writing an equation for a line ($y = mx + b$), or with exponential functions ($y = e^{kt}$). And with a little algebra, we can rearrange those equations to solve for ANY of the variables in them.

Although this may seem like magic, you don't have to be a "mathemagician" to do this. This page is designed to give you some tools to call upon to help you to learn some simple steps to help you to solve an equation for any of the variables (letters that represent the element or quantity of interest).

► Show credits

The module emphasizes the importance of manipulating equations before inserting numbers; thereby creating a "new" equation that can be used in a variety of applications. This page also includes a review of rules for algebraic manipulation with some conceptual explanation of why it works. A step-by-step procedure is subsequently embedded in a worked practice problem (with hidden answers).

Some simple steps for manipulating equations

Here are some simple steps for manipulating equations. Under each step you will find an example of how to do this with an example that uses the geologic context of [density](#) (a measure of mass per unit volume).

1. Assess what you have (which of the variables do you have values for?, what units are present?, etc.). **DO NOT plug in any numbers yet!**
► Show me how to do this
2. Determine which of the variables you want as your answer. (What is the question asking you to calculate? What is the unknown variable?)
► Show me how to do this
3. Rearrange the equation so that the unknown variable is by itself on one side of the equals sign (=) and all the other variables are on the other side. **RULE #1: you can add, subtract, multiply and divide by anything, as long as you do the same thing to both sides of the equals sign.**
► Show me how to do this
4. **NOW plug in the numbers!** Replace known variables with their values and *don't forget to keep track of units!*
► Show me how to do this
5. Determine the value of the unknown variable by performing the mathematical functions. That is, add, subtract, multiply and divide according to the equation you wrote for step 2.
► Show me how to do this
6. Ask yourself whether the answer is reasonable in the context of what you know about the geosciences and how much things should weigh.
► Show me how to do this

Practice Problems Page

(<http://serc.carleton.edu/mathyouneed/equations/ManEqSp.html>)

When students have completed the introductory page, they are directed to the practice problem page where they find several other geoscience-related practice problems. A series of practice problems using the procedure in at least three distinct contexts is linked from the Introduction Page and are included in a linked PDF file that includes steps for solving them. The Practice Problem page for Rearranging Equations includes worked problems involving simple rates, density, and a more complicated isostasy equation. Each example problem is worked through using the steps outlined on the Introduction Page (see above) with the answers “hidden” until the student clicks on a “show” button to see how to do each step. When they have completed the problems, students can follow links to other examples at similar websites, or to the assessment.

Solving for any variable... Rearranging Equations - Practice Problems

Practice rearranging equations below using the “rules” that you have just learned. Answers are provided (but try doing them on your own before peeking!) You can [download a sheet with all the questions](#) (Acrobat (PDF) 127kB Jul25 09) so you can print them out to try on your own.

Velocity, distance and time

Many problems in the geosciences deal with the concept of velocity, from stream flow to plate motion. Being able to manipulate the equation for velocity ($v = d/t$) gives you a powerful tool for understanding the world around you. And there are two other equations that you can get by rearranging the equation that you probably already know for velocity (also rate)!

Problem 1: Generally, we know the equation for velocity (a rate) to be:

$$v = \frac{d}{t}$$

Where v = velocity, d = distance and t = time.

This equation can be rearranged so that you have an equation for distance (d) and time (t).

1. **Rearrange the velocity equation to create an equation for distance (d).**
▶ [Show me how](#)
2. **Rearrange the velocity equation to create an equation for time (t).**
▶ [Show me how](#)

Use the equations that you manipulated above to solve the following problems:

Problem 2: A wave traveling downward from the surface of the ocean at 1.5 km/sec takes six seconds to reflect off the ocean floor. How deep is the ocean at that site?

▶ [Show me how to calculate the depth](#)

Problem 3: Imagine that you are working with Ms. Homeowner to understand the groundwater flow in her area. She is particularly interested in an underground tank that is located 2.6 km from her home. You have measured the velocity of the groundwater to be 0.033 km/day. About how long will it take any contaminants leaking from the tank to reach Ms. Homeowner's well?

▶ [Show me how to calculate how long](#)

▶ [Show credits](#)

Assessment (post-module quizzes)

(<https://www.wamap.org/> - Requires account, contact authors for information)

Instructors create their own, course-specific assessments. Assessment questions that have been tested and written by users of TMYN can be found in the WAMAP library. They include questions in which students choose the rearranged equation they will use and then apply it to solving the given problem, promoting use of the algorithm (Table 2).

Table 2
Examples of Problems Used in *The Math You Need* Assessments

Unit Conversions	
<p>Sample problem</p> <p>You have noticed that, on a map, a group of islands makes up a small chain that decreases in age toward the southeast. When you measure the distance and differences in age, you determine that the tectonic plate over the hot spot has moved 30 kilometers in a million years.</p> <p>1) Choose one or more conversion factors that can best be used to convert 30 km/Myr (kilometers per million years) to cm/yr (centimeters per year).</p> <p> ☐ 1min/60sec ☐ 1hr/60min ☐ 100cm/1m ☐ 1km/1000m ☐ 60min/1hr ☐ 1Myr/1000000yr ☐ 1000m/1km </p> <p>2) Now convert 30 km/Myr to cm/yr : _____ cm/yr</p>	<p>Notes</p> <p>This multi-step quiz question is one of the most commonly used in the TMYN question library. Note that the 30 km/Myr in the question text is a randomly selected value between 20 and 200 km/Myr</p>
Estimating a Best- Fit line	
<p>Sample problem</p> <p>The graph shows the location and age of a volcanic hotspot relative to the location of the present day volcano. The x-axis (horizontal) has distance (in 100's of km) from present day volcano plotted and the y-axis (vertical) has age in millions of years. The trend of the data is generally linear. Estimate the location of the linear trend (plot a best fit line).</p>	<p>Notes</p> <p>Using the software, the student plots a best-fit line. WAMAP evaluates the "fit" of the line based on parameters set by the instructor. If a student "connects the dots" (a common misconception) no credit is given.</p>
Rearranging Equations	
<p>Sample problem</p> <p>The equation for isostasy (the height and thickness of crust based on density) is:</p> $H_{above} = H_{total} \cdot \left(1 - \frac{\rho_{crust}}{\rho_{mantle}}\right)$ <p>where H_{total} is the thickness of the crust, ρ_{crust} is the density of the crust, ρ_{mantle} is the density of the mantle, and H_{above} is the height above the mantle equilibrium level. 1) Rearrange this equation to solve for H_{total}. Choose the correct solution:</p> <p> ☐ $H_{total} = \frac{H_{above}}{\left(1 - \frac{\rho_{crust}}{\rho_{mantle}}\right)}$ ☐ $H_{total} = \frac{H_{above}}{\left(1 - \frac{\rho_{mantle}}{\rho_{crust}}\right)}$ ☐ $H_{total} = \frac{H_{above}}{\left(1 + \frac{\rho_{crust}}{\rho_{mantle}}\right)}$ ☐ $H_{total} = \frac{H_{above}}{\left(1 + \frac{\rho_{mantle}}{\rho_{crust}}\right)}$ </p> <p>2) Using this equation, calculate the thickness of the crust under Mt. Everest (elevation 8.85 km), if H_{above} is 16 km (remember, sea level is NOT the mantle equilibrium level), ρ_{crust} is 2.67 g/cm³, and mantle is 3.3 g/cm³.</p>	<p>Notes</p> <p>Another example of a multi-step quiz question. Crust and mantle densities are randomly generated within a narrow range of reasonable values.</p>

Each TMYN module culminates in a graded online post-module quiz with questions that include intermediate steps in the algorithm as well as contextual problems. Quiz questions associated with TMYN are framed in the context of geoscience application. There are no questions that simply ask the student to complete mathematical operations (e.g., “solve for x ”); instead, quiz (and pre- and post-test) questions take the form of “word problems” that require assessment, decision-making, and evaluation of one’s answer (Table 2). Instructors administer quizzes using the free, open-source Washington Mathematics Assessment Program, WAMAP.² The majority of students in this study were allowed to take the post-module quizzes multiple times, promoting mastery, success and self-efficacy at solving scientifically relevant problems.

Study Design

Our study assesses whether the use of TMYN effectively (1) improves geoscience students’ basic mathematical skills, (2) helps students apply mathematical skills to contextual problems, and (3) provides appropriate support and skill development (i.e., levels the playing field) for geoscience students with diverse incoming skills. To test the effectiveness of TMYN, we used changes from pre- to post-test at the student level as a measure of learning gains and thus the effectiveness TMYN.

Participants/Breadth of Sample

This study was conducted from Fall 2010 through Fall 2013 and included 106 courses offered at 37 institutions (Table 3). The institutions are diverse, ranging from highly selective to open-door; approximately 60% are bachelor’s degree-granting institutions and offered 56 of the 106 courses in this study (Table 3). TMYN was used in multiple semesters/quarters across the range of institutions, illustrating faculty perception that TMYN is a valuable and effective resource for most students.

Faculty from institutions included in this study attended one or more workshops focused on incorporating TMYN into a pre-existing course (Wenner et al. 2011). During the workshop, faculty applied lessons learned from pilot studies and prior implementations of TMYN, designed an implementation by modifying their syllabus, and adapted course materials to include appropriate TMYN modules.³ Workshop participants also designed a protocol for the administration of pre- and post-tests as well as the implementation of modules and their associated quizzes. Workshop facilitators guided faculty in effective practices

² <https://www.wamap.org/> (last accessed June 1, 2015)

³ <http://serc.carleton.edu/mathyouneed/about/implementations.html> (last accessed June 1, 2015)

such as integration of TMYN with the course (Wenner et al. 2011) and revisiting mathematical concepts multiple times in multiple contexts (Manduca et al. 2008; Wenner et al. 2009).

Table 3:
Institutions and Number of Classes (*n*) Implementing TMYN

<i>College or University</i>	<i>% admitted</i>	<i>total completers*</i>	<i>classes</i>
<i>4-year College or University</i>			
Trinity College, CT	34%	12	1
SUNY Geneseo	36%	306	3
Lafayette College, PA	40%	42	2
Baylor University, TX	40%	392	3
SUNY Oneonta	43%	17	1
California University of Pennsylvania	45%	91	3
West Chester University, PA	47%	87	3
Boston University, MA	51%	37	5
Hofstra University, NY	54%	19	2
California State University-East Bay	61%	6	1
Eastern Kentucky University	66%	21	3
Fitchburg State University, MA	69%	83	5
Ursinus College, PA	70%	17	1
Fort Lewis College, CO	72%	184	10
Central Michigan University	73%	157	2
University of Washington - Tacoma	78%	29	1
University of Wisconsin - La Crosse	78%	68	1
University of Wisconsin Oshkosh†	79%	220	2
University of Maine at Farmington	82%	35	2
Morehead State University, KY	89%	42	2
University of Texas at El Paso	99%	173	3
<i>2-year College</i>			
Hillsborough Community College, FL	100%	81	5
Harold Washington College, IL	100%	2	1
McHenry County College, IL	100%	144	8
Community College of Baltimore County, MD	100%	23	2
North Hennepin Community College, MN	100%	9	1
Rochester Community and Technical College, MN	100%	5	1
Wake Technical Community College, NC	100%	272	7
Bergen Community College, NJ	100%	58	4
Ulster County Community College, NY	100%	8	1
Linn Benton Community College, OR†	100%	111	5
University of South Carolina Lancaster	89%	41	2
Lone Star College, TX	100%	78	3
Austin Community College, TX	100%	50	4
Patrick Henry Community College, VA	100%	25	2
Highline Community College, WA	100%	32	2
Central Wyoming College, WY	100%	4	2

† *more than one instructor*

* *students who completed all or all but one of the assigned modules in their course*

Courses included in this study covered a range of geoscience topics; common first-year introductory courses (Physical Geology, Environmental Geology and Earth System Science) made up approximately 63% ($n=67$) of all implementations. Other introductory courses ($n=28$) were more varied in topic, with titles such as Meteorology, Natural Hazards, Physical Geography and Oceanography. The remaining 11 courses were upper-level courses and included Hydrology ($n=3$), Geomorphology ($n=1$), Structural Geology ($n=4$) and Geological Methods ($n=3$). In total, 4486 students were enrolled in the 106 courses involved in this study; individual course enrollments ranged from 5 to 202 students. Although courses were offered at a variety of levels, we examined all uses of TMYN in this study because we observed no significant difference between pre-test scores and subsequent achievement for introductory and upper-level students (Wenner et al. 2012). The variety of course topics for which faculty desired additional mathematical support emphasizes the need for resources such as TMYN in the geosciences at all levels and underscores the diversity of students who can benefit from the implementation of TMYN.

Use of TMYN

In the courses included in this study, students completed a pre-test prior to engaging with TMYN; engaged with each module relevant to their course and took the associated post-module quiz; and then took a post-test when all the intervention and associated course content were completed. Equivalent pre- and post-tests consisted of 10-25 questions relating to the assigned modules and assessed quantitative knowledge and the ability to transfer that knowledge to geoscience content. Equivalency in pre- and post-test questions was determined by the format and quantitative skills of the questions; in some cases questions were identical, but in most cases varied slightly by randomizing specific numerical values used in questions (Table 2). In all but five cases, the pre- and post-tests were administered online, sometimes in a computer-equipped classroom; all post-module quizzes were administered using WAMAP.

Because we wished to provide flexibility for instructors to incorporate mathematical skills that span the breadth of topics covered in geoscience courses, instructors designed their own pre- (and equivalent post-) tests, as well as post-module quizzes so that they included only topics that were covered in the associated course. Each course varied in assigned modules, pre- and post-test questions, and course subjects; thus, the student sample was normalized using standard Z scores (Abdi 2007) so that we could compare results across implementations. Three to eight modules were used in each implementation. Pre-test, post-test and post-module quiz scores were converted to percent correct for analysis.

Measuring engagement and effectiveness

If geoscience students are to gain skills from TMYN, they must engage with and complete the material contained in the modules. Because we wished to assess the effectiveness of TMYN modules at improving skills, we developed a measure of student engagement with the material. Only students who took post-module quizzes for all or all but one of the assigned modules were considered to have completed the intervention (we call them “completers”) and were included in our analysis of learning gains due to the application of TMYN in conjunction with a course. Based on this criterion, 3408 students completed the intervention and 2979 took both the pre and post-test (Table 4A).

In our desire to ensure that all students had maximum access to tools that could help them to succeed, we chose to administer the intervention to all students, precluding a formal randomized control sample. However, 311 students completed both a pre- and post-test but did not engage with a minimum number of TMYN modules, providing a quasi-control group. Although this group is not a randomized control, this group of non-completers (1) received the same information outside of the module as those students who engaged with the modules; and (2) appears representative of the students in the study because average pre-test scores for both groups are similar (Table 4). Thus, we use these non-completers to assess the effectiveness of the intervention at improving learning gains.

Normalizing pre -test data (Z_{pre})

Because we wanted to maximize use and allow for flexibility in both topic and coverage, instructors tailored the pre-test to their implementation. To be able to compare diverse interventions, we computed a standard Z score (Abdi 2007) using the individual course pre-test mean and standard deviation to calculate students’ normalized pre-test scores (Z_{pre}):

$$Z_{pre} = \frac{score_{pre} - mean_{course}}{SD_{course}} \quad (1).$$

where $score_{pre}$ is the individual student pre-test score, $mean_{course}$ is the course pre-test mean, and SD_{course} is the standard deviation of pre-test scores for the individual course. For the purposes of this study, we subdivided students in the study into four groups based on their Z_{pre} scores (Table 4): Group 1 with Z_{pre} less than -1.0 (much below the class mean); Group 2 with Z_{pre} between -1.0 and 0.0 (below the class mean); Group 3 with Z_{pre} between 0.0 and 1.0 (above the class mean), and Group 4 with Z_{pre} greater than 1.0 (much above the class mean; Table 4). These designations will be used throughout the paper.

Table 4:

A: Pre- to Post-test Gains and Mean Normalized Gain* (Hake, 1998) for Completers Disaggregated by Z_{pre}^{**}										
Group (range of Z_{pre}^{**})	pre-test (n)	pre- & post-test (n)	mean NG*** (%)	NG negative (n)	NG positive (n)	NG = 0 (n)	pre-test =100% (n)	n excluded**** (NG)	Average pre-test score	Average post-test score
Group 1 (< −1)	506	430	44%	32	394	4			36%	64%
Group 2 (−1 to 0)	1068	915	38%	119	782	12			55%	72%
Group 3 (0 to 1)	1325	1173	25%	311	820	33	11	12 (−468%)	73%	80%
Group 4 (>1)	509	461	11%	144	237	27	53	20 (−672%)	85%	88%
Totals (n)	3408	2979	2883	606	2233	76	64	32		
B: Pre- to Post-Test Gains and Mean Normalized Gain* (Hake, 1998) for Non-Completers Disaggregated by Z_{pre}^{**}										
Group 1 (< −1)	122	80	24%	9	69	2			31%	48%
Group 2 (−1 to 0)	179	95	28%	18	70	7			52%	65%
Group 3 (0 to 1)	158	108	7%	30	69	9			71%	74%
Group 4 (>1)	48	28	-21%	7	10	2	8	1 (−467%)	83%	80%
Totals (n)	507	311	302	67	215	20	8	1		

* Average of normalized gain [eq. (2)] for all students within a given Z_{pre} category (Gery 1972, Hake 1998; Kaiser 1989; Williams and Zimmerman 1996).

** Z_{pre} is the difference between individual pre-test score and course mean divided by standard deviation [eq. (1)]; a standard statistical measure)

*** 32 (~1%) completers and 1 (<<1%) control student with normalized gains below -250% (meaning they lost more than 2.5 times the points between their pre-test score and 100%) were excluded from these calculations (see text for justification)

Results

Pre- and post-test scores

Table 4 shows pre- and post-test scores (far right columns) for completers (A) and non-completers (B) with scores for both. Course means and individual pre-test scores for 3408 completers and 507 non-completers were used to calculate each student's Z_{pre} (Eq. (1); Table 4A). Analysis of student scores based on Z_{pre} group designations shows the disparity in student abilities at the outset of a geoscience course. Average completers' pre-test scores subdivided by Z_{pre} show a nearly 50 percentage point spread. Students in Group 1 ($n=506$) averaged 36% on the pre-test whereas students in Group 4 ($n=461$) scored an average of 85% on the pre-test (Table 4A). For the non-completers, the spread is only slightly greater (52%) with Group 1 scoring 31% and Group 4 scoring 83% (Table 4B).

Average post-test scores, which measure student achievement with the use of TMYN, are also shown in Table 4. Post-test scores for completers range from 64% (Group 1) to 88% (Group 4); each Z_{pre} designation shows improvement from pre- to post-test. For the non-completers, student post-test scores vary from 48% to 80%, and Group 4 shows a decline of 3 percentage points from pre- to post-test. Although pre-test scores are relatively similar between completers and non-completers in the same group, post-test scores for non-completers are significantly lower than for their counterparts who completed the intervention.

Normalized gain scores

Normalized gain is a common way to measure learning gains (e.g., Gery 1972; Hake 1998). It is calculated as a percentage using a student's increase from pre-test to post-test divided by the maximum possible gain (Gery 1972, Hake 1998):

$$NG (\%) = \frac{score_{post} - score_{pre}}{100\% - score_{pre}} \quad (2).$$

where NG = percent normalized gain; $score_{post}$ = post-test score (%); and $score_{pre}$ = pre-test score (%). Normalized gain scores are used in this analysis rather than difference scores because the former correlates less well with pre-test scores ($corr. coeff. = -0.221$; Fig 2B) than the latter ($corr. coeff. = -0.530$, Fig. 2A) (Kaiser 1989). If the difference between the pre- and post-test score were to be used, initially high-scoring individuals' changes would be muted (Fig. 2A). An additional advantage to using normalized gain is that by choosing a change measurement that is poorly correlated to the pre-test value, the reliability of this difference is greater (Williams and Zimmerman 1996).

Figure 2. Plots showing Z_{pre} (symbol color) and correlation between pretest score and (A) simple difference (pre-test - post-test with student scores excluded from calculations of average NG (Table 4) shown in orange (extreme NG) and black (perfect pre-test) diamonds. This plot illustrates the muting of small but substantial changes in scores for students who score high on the pre-test. Note the clustering of green and blue points for high pre-test scores (B) pre-test score vs. normalized gains (NG). White field shows student with positive gains or no change, approximately 78% ($n=2309$) of students. Gray field shows students with negative gains. Orange diamonds in A plot off the bottom of the gray field.

Normalized gain scores for completers and non-completers in this study with both pre- and post-test scores ($n=2979$ and $n=311$, respectively) were calculated using Equation (2). Table 4 shows scores subdivided into number of students with positive, negative or zero NG and average NG for each group. Positive NG scores record student improvement throughout the semester; negative NG scores indicate that students had a lower score on the post-test than on the pre-test. Mean normalized gains for each Z_{pre} group are plotted for comparison in Fig. 3. Note that NG cannot be computed for students who score 100% on the pre-test (denominator would be zero); therefore, 64 completers who had perfect pre-test scores (~2%; Fig. 2A black symbols) and 8 non-completers (2.5%) were excluded from analysis of NG scores (Table 4; Fig. 3).

Figure 3. Normalized gains (subdivided by Z_{pre}) for completers (black) and non-completers (gray) with both pre- and post-test scores. See Table 4 for n in each group.

Using normalized gain scores can exaggerate small negative changes for students with high pre-test scores, resulting in outliers with extreme negative NG scores (e.g., one student in our sample who scored 99% on the pre-test and 78.8% on the post-test resulting in a $NG = -2020\%$). Large negative normalized gains, when included in mean calculations, mask the true effectiveness of the intervention for the majority of high-scoring students. For the purposes of assessing learning gains, we omit 32 completers (1.1%; orange symbols Fig. 2A) and 1 non-completer (0.3%) whose normalized gain scores were equal to or less

than -250% . All large negative gains are for students who scored above the mean on the pre-test: 12 in Group 3 and 21 (plus one non-completer) in Group 4. Exclusion of these outliers changes the average *NG* from -22% to $+11\%$ for Group 4 and from $+21\%$ to $+25\%$ for Group 3 completers.

Fig. 3 shows calculated mean normalized gains for completers and non-completers in each group (Table 4). With the exclusion of the students discussed above, the sample size for *NG* drops to 2883 completers and 302 non-completers. Completers show positive mean *NG*s for all groups, with those who score below the mean on the pre-test (Groups 1 and 2) showing greater gains (44% and 38% , respectively) than their higher-scoring counterparts (Group 3: 25% ; Group 4: 11%). Non-completers ($n=302$) who did not fully engage with the intervention realized diminished normalized gains relative to their fully engaged counterparts in this study. Although Groups 1, 2 and 3 show nominal learning gains (24% , 28% , and 7% , respectively), Group 4 – the highest scoring individuals – averaged negative *NG* (-21% ; Fig. 3).

Discussion

TMYN effectively improves mathematical skills

The effectiveness of TMYN at improving students' skills is illustrated in Fig. 3. Faculty included in this study used an integrated approach, requiring all students to complete the intervention regardless of pre-test score, a decision based on prior research revealing that completion rates dropped when high-performing students were given the option to forego the modules (Wenner et al. 2011). Completers (black bars) show improvement (on average) across all skill levels whereas non-completers (gray bars) realize much lower gains (and, in Group 4, gains are actually negative). Non-completers' average scores on the pre-test (Table 4) illustrate that these students (although a considerably smaller sample) represent a relatively good cross-section of the students who participated in the study. Non-completers and completers received identical course information; yet non-completers did not fully engage with the tutorials. Students who do not engage with the program consistently score lower on the post-test (Table 4) and realize lower normalized gains (Fig. 3) than their engaged counterparts. The combination of positive learning gains plus consistent learning gains for completers, and lower *NG* and post-test scores for the quasi-control group support the conclusion that learning gains are, at least in part, the result of employing TMYN tutorials in conjunction with a geoscience class. Furthermore, application of the intervention to all students seems to be justified by the small sample of students with pre- to post-test changes who did not engage with the modules.

TMYN helps students apply mathematical skills to geoscience

Mean normalized gains reveal that TMYN modules can help students at all incoming levels to successfully apply mathematics to contextualized quantitative science problems (Fig. 3; Table 4). Because pre- and post-tests included mathematical problems in the context of geoscience, individual learning gains can illustrate increased transfer of skills from mathematics to geoscience. Individual normalized gains vs. pre-test scores for completers are plotted on Fig. 2B; points that fall in the white box represent positive or no change (80%; $n=2309$; Table 4A); completers with negative *NG* plot in the gray portion of the plot (20%; $n=574$). Students who initially lack quantitative skills (based on low pre-test scores; red and yellow symbols; Fig. 2B) show the greatest improvements with the implementation of TMYN; nearly 89% of low-scoring students (1129 of 1345) showed positive normalized gains and cluster in the white field. Although a larger proportion of Groups 3 and 4 (green and blue symbols respectively; Fig. 2) have learning gains that reflect lower post-test scores (gray box), a majority of both groups showed positive gains (Group 3=70%; Group 4=51%; Table 4). Individual student learning gains on pre- and post-test questions suggest that TMYN supports the successful transfer of students' basic mathematical skills to geoscience topics. Thus, a majority of students who engage with the material, no matter where their pre-test scores fall in relation to their peers, realize learning gains.

TMYN levels the playing field

The use of TMYN reduced the nearly 50 percentage point difference in pre-test scores between the highest and lowest performing group to less than 25 percentage points between the same groups of students on the post-test (Fig. 4). The average change from pre- to post-test score for 430 students in Group 1 was from 36 to 64% – a positive change of 28 percentage points – whereas the average post-test score for the 461 students in Group 4 went from 85 to 88% (Fig. 4; Table 4). The intervening groups showed intermediate change – from 55% to 72% for Group 2 and 73 to 80% for Group 3 students (Fig. 4). Whereas all groups averaged some improvement between pre- and post-test, students who scored lowest on the pre-test showed greater gains than higher-performing students indicating that the integration of TMYN in a course closes the gap between low- and high-performing students (Fig. 4). Indeed, the gap between high- and low-scoring students was reduced by more than 50% – from 49 percentage points on the pre-test to 24 percentage points on the post-test (Fig. 4) – suggesting that engagement with TMYN helps to “level the playing field” for students of differential abilities.

Figure 4. Average pre- and post-test scores for completers in 106 courses that used TMYN ($n=2979$). Colors represent different groups with warm colors representing low scoring students and cool colors representing high scoring students: red: Group 1 (more than 1 SD below mean); yellow: Group 2 (0-1 SD below mean); green: Group 3 (0-1 SD above mean); blue: Group 4 (>1 SD above mean). Note the wide disparity among pre-test scores that is more than halved (from 49-24 percentage points difference) from pre- to post-test, illustrating the leveling of the playing field for students using TMYN.

Conclusions

Our findings reinforce the idea that students who interact with context-specific quantitative problems, such as those embedded in TMYN, realize learning gains and improve their quantitative skills. Individual learning gains on contextualized pre- and post-test questions illustrate that, when quantitative problem solving is integrated into a science course, modules that support quantitative learning can promote knowledge transfer from mathematical concept to geoscience contexts. Student improvement from pre- to post-test across all levels of initial quantitative skills indicate that The Math You Need, When You Need It is effective at “leveling the playing field,” no matter a student’s prior preparation. Furthermore, the disparity in post-secondary students’ mathematical preparation is not a problem specific to the geosciences; many general science courses require basic quantitative knowledge. Thus, although the current modules are solely in the context of the geosciences, we contend that the support provided by quantitative

modules integrated into a course could generalize to a variety of science disciplines.

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