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Envisioning the Future of Mathematics Education in Uncertain Times

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AN ESTIMATION GAME TO PROMOTE SECONDARY STUDENTS' CLIMATE CHANGE UNDERSTANDING USING DATA AND VISUALIZATIONS

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Data and data visualizations have the potential to shift learners' attitudes and conceptions about controversial science topics. However, many people, particularly secondary students, struggle to make scientific meaning from data. This design-based research project aimed to support data literacy and science learning by developing an online estimation game to support secondary students' understanding of climate change with data and data visualizations. Over the course of three design iterations, we interviewed 12 racially diverse secondary students and documented the design of a climate change number estimation game. Inductive coding analysis illustrated dimensions of students' (a) estimation strategies employed (e.g., drawing from prior knowledge, mental computation, wildly guessing), and (b) emotions experienced while estimating climate change numbers (e.g., emotions about climate change vs. about performance).

Keywords: data literacy; design-based research; numerical estimation; secondary education

Scientific data visualizations—such as maps, charts, and graphs—can communicate critical socioscientific information to the public (Allen, 2018; Harold et al., 2016). However, many people lack the quantitative reasoning skills needed to interpret these visualizations (Börner, et al., 2016; Peters et al., 2006; Thacker & Sinatra, 2019). Secondary students, in particular, struggle with number magnitudes using conventional number line representations (Doyle, 2015; Vamvakoussi & Vosniadou, 2004; 2007; 2010; Wilensky, 1991). This magnitude knowledge predicts math and science achievement (Booth & Siegler, 2006; Sasanguie et al., 2012; Siegler & Booth, 2004; Siegler et al., 2012), and students' inability to use visual representations to compare rational numbers can lead to misinterpretations of science topics (Siegler, 2016).

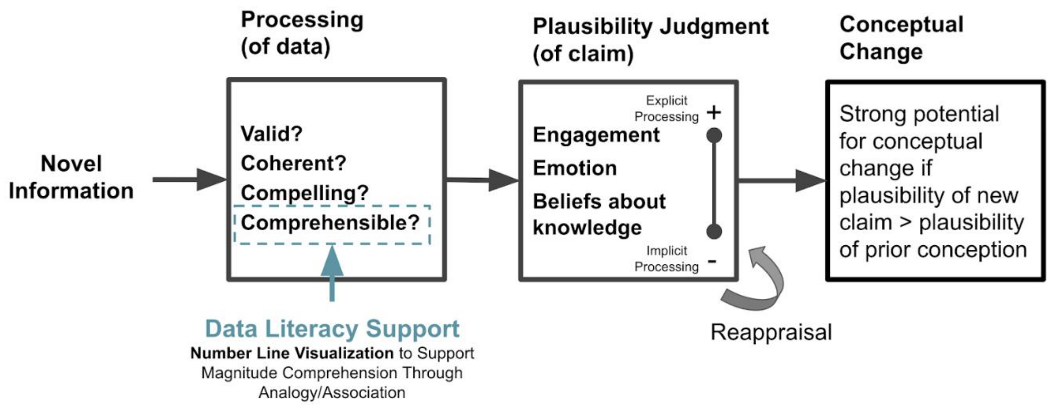
A relevant topic relying on quantitative evidence is climate change. National science standards require students to understand quantities, tables, and graphs related to human-induced climate change (NGSS, 2013). However, students have serious misconceptions about climate change (Dawson & Carson, 2013; McNeil & Vaughn, 2012). There is a need for learning contexts that support climate change understanding and data literacy. Several approaches, such as micro-interventions with surprising numbers about climate change, support learning (Ranney & Clark, 2016; Thacker & Sinatra, 2022), though evidence thus far uses undergraduate samples.

The current project developed an intervention to shift secondary students' climate change misconceptions by leveraging data visualization skills and documenting design choices for integrated STEM learning. The intervention used number line visualizations to support data literacy and climate change learning and investigated estimation strategies students used therein.

Theoretical Framework

To explain how novel data and data visualizations might help shift scientific misconceptions, we integrate theories of conceptual change and numerical development. *Conceptual Change* involves restructuring conceptions to align with scientific consensus (Dole & Sinatra, 1998). The Plausibility Judgments for Conceptual Change (PJCC) model (Lombardi et al., 2016) posits that novel information can shift conceptions if it is *comprehensible*, *coherent*, *compelling*, and *valid*. More explicit plausibility judgments—which are influenced by motivation, engagement, and emotion—increase the likelihood of conceptual change (see Figure 1 for a summary).

Figure 1.
Conceptual Change Process Model



Empirical research shows that novel data can inspire conceptual change about climate change. Estimating climate change numbers before presenting the true values can reduce undergraduates' misconceptions (Thacker & Sinatra, 2022; Thacker, 2023). Further, instruction on data-literacy skills can enhance knowledge gains (Thacker, 2023; Thacker et al., 2024). However, no research thus far has tested this approach with secondary students nor assessed the benefits of supplementing the experience with data visualizations.

Data visualizations can support understanding of scientific quantities and developing of numerical knowledge. Siegler's (2016) *Integrated Theory of Numerical Development* posits that people develop an accurate understanding of number magnitudes and their relationships as they connect numbers (e.g., representing rising global temperatures) to the things that those numbers refer to (e.g., global climate change). Such connections between numbers and their referents happen through processes of analogy and association, as facilitated by conventional representations and visualizations. The linear number line is central to representing real numbers and helps students compare magnitudes and understand abstract concepts (Van De Walle et al., 2013). This can support math and science learning, retention, and engagement (Gunderson et al., 2012; Schwartz & Heiser, 2006; Siegler, 2016; Saxe et al., 2013; Stevens & Hall, 1998).

The current research concentrates on the design of an online intervention presenting secondary students with novel climate change data. The study investigates using number line visualizations to enhance student comprehension of climate change data, math and science learning, and identifies strategies students employ that support this learning. Namely, we ask:

1. *How can a learning intervention be developed to leverage number line estimation skills for the learning of climate change science among secondary students?*
2. *What numerical estimation strategies do students employ when estimating climate change numbers? And how do they respond when presented with the true value?*

Methods

To answer our research questions, we used a design-based research (DBR) methodology (Anderson & Shattuck, 2012; Hoadley & Campos, 2022) to guide the design of an online intervention that we call the "Estimation Game." Typical of DBR, the design, implementation, and revision occurred over several iterations (Bakker, 2019; Cobb et al., 2003).

We revised an existing online estimation game (Thacker et al., 2024), where undergraduate students estimated 12 climate change numbers before being shown the scientifically accepted number. Half of the prompts included given benchmark values (e.g., "hints") that learners could arithmetically manipulate to estimate unknown values. After estimating each value, a pop-up window would appear displaying the true number, accuracy feedback (one to five "gold stars"), an explanation of the climate change number to help students contextualize the quantity in terms of students' prior knowledge, and links to sources of the information to improve credibility.

For this study, we aimed to modify this design to improve data comprehensibility and engagement. Modifications included (a) personalized feedback via a number line visualization to help students compare their estimates with the true value, (b) revised text that is more suitable for secondary students, and (c) a revised look-and-feel to be more game-like. This work resulted in an online, open-source estimation game for secondary students with number line visualization feedback (ianthacker.com/design.html). For a related quantitative study, see Thacker (in press).

Participants and Procedure. The intervention design, implementation, and revision occurred over three iterations. We conducted 12 one-on-one "think-aloud" interviews (Desimone & Le Floch, 2004) via Zoom with a diverse sample of secondary students (grades 7-12) from a southern U.S. metropolitan area. Students identified as female (50%), male (50%), Hispanic (60%), White (58%), two or more races (33%), and Black (8%). Each iteration included pretests, engagement with the game, posttests, and a demographics questionnaire.

Survey Materials. Students completed measures of climate change knowledge and plausibility at pretest and posttest. The knowledge measure assessed the scientific consensus on climate change using a five-point agreement scale (Lombardi et al., 2013). The plausibility perceptions measure assessed endorsements related to human-induced climate change using a seven-point scale (Lombardi et al., 2012).

Analysis. Qualitative analysis occurred in four waves: three after each design iteration and a fourth after all data was collected. Interviews were transcribed and analyzed. Interviewers wrote analytical memos based on open analyses of each transcript, and conclusions informed modifications to the Estimation Game. After three iterations, recordings were open-coded for student thinking dimensions (Corbin & Strauss, 2004; Saldaña, 2021). Themes centered around students' quantitative reasoning strategies and emotions experienced during the game.

Findings

Survey results showed growth from pretest to posttest. At pretest, students had an average knowledge score of 2.4 of 5 and plausibility perception score of 4.87 of 7. Posttest scores improved to 2.91 of 5 for knowledge and 5.08 of 7 for plausibility.

RQ1: Design of an Open-Access Data Estimation Game with Number Line Visualizations

Three design iterations informed several game modifications. The first design iteration redeployed the central design features of the original intervention created by Thacker et al. (2024). We asked participants to estimate 12 climate change numbers. After making each estimate, a pop-up window would display the actual value along with accuracy feedback (one to five gold stars), an explanation of the true value, and links to sources of the information. At the end, a summary page provided an overview of all estimated items and accuracy ratings.

Four key improvements were introduced on top of the original design prior to the first round of interviews. First, we modified the accuracy feedback to also present students with a linear number line visualization illustrating each estimate alongside the true value to facilitate comparisons between the two and boost comprehension. Second, we adjusted the procedure for calculating accuracy feedback to present students with gold stars indicating order of magnitude error rather than absolute error, which is a more generous assessment of estimation accuracy and has been used in similar research (Bröder et al., 2022). Third, to make the intervention more "game-like" we modified the progress bar to include an earth icon, the summary page to provide students with a "final score" indicating the sum of their accuracy ratings, and we updated the "look and feel" of the web app to include more color and animation.

RQ2: How Students Responded to the Intervention

Inductive coding revealed themes in students' estimation strategies and emotional responses. Estimation strategies included drawing from prior knowledge, mental computation, and wild guesses. Emotional responses varied from relief, sadness, and surprise about climate change information to excitement or disappointment about their performance. A summary of related results are presented in Table 1.

Table 1. *Summary of Themes Related to Student Reactions to the Estimation Game*

Dimension	Sub-Dimension	# of Students	Example Excerpts from Student Interviews
Theme 1: Strategies for Estimating Climate Change Quantities			
Prior Knowledge	Educational	1	I was in geography and I saw a picture from 2009 to 2020, and it raised by a lot, so I'll say, say 65 inch increase.
	Personal	7	It's really cold right now… so [I'll estimate] maybe like 7
	Prior item	6	I'm going to use the same answer that I used in my first question.
	Vague	11	I remember hearing somewhere… it was 30.
Mental Computati-on Applied to a Given Value	Extrapolation	10	[Reading hint] Global sea levels rose by 1 inch between [1900 and 1920] that's not a lot…. But [now] it's more… like 5 or 6.
	Arithmetic	9	I would just say 12. I'm just going to multiply by four.
	Unspecified	4	I think it's gone down [compared to what was given in the hint]
	Rounding	1	So we'll round the 53 to 50…
Wild Guess	Wild Guess	12	I'd say four. Wild guess
Theme 2: Emotional Response to New Information			
Emotions **(about climate change)**	Relief	5	I'm glad that more countries are [committing to climate action] than I thought.
	Sadness	8	Geez [glaciers are melting], well that's sad.
	Surprise	8	I am very surprised and happy about it too. Huh. That is a nice surprise to know that I am very wrong.
Emotions **(about**	Excitement	6	Amazing job. I was so close. *claps* Look at that. It was 151%. Yay, I got five stars!

performance)	Disappointment	5	Seriously? 5 billion times, I got one star. That's my lowest score. That's really sad.

Contributions

We sought to design an Estimation Game and explore the strategies that diverse secondary students use when estimating climate change data. The intervention, guided by theories of conceptual change and numerical development, reduced climate change misconceptions and increased climate change plausibility perceptions. We found that, as students estimated numbers, they tended to draw from their prior knowledge and/or employ mental computation strategies, supporting the idea that estimating real-world quantities may provide opportunities for students to coordinate their magnitude knowledge and prior knowledge in such a way that is mutually beneficial (Siegler, 2016). Future research might explore relationships between estimation strategies and emotional responses and their impact on STEM-integrated learning.

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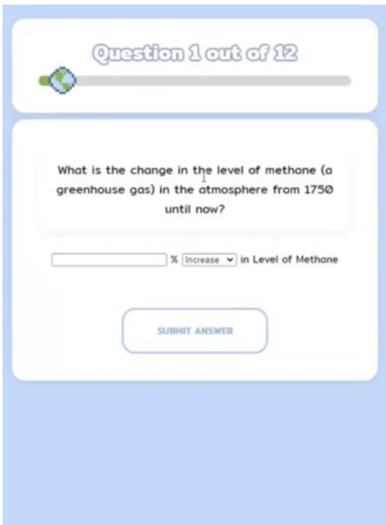
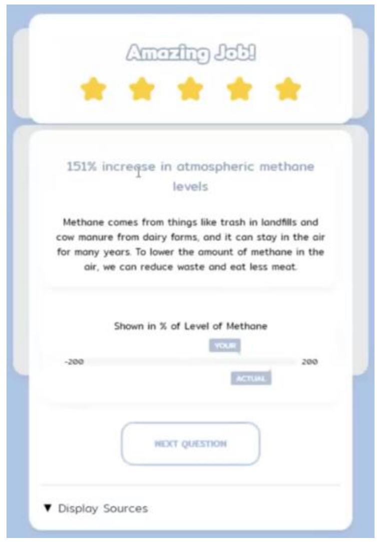
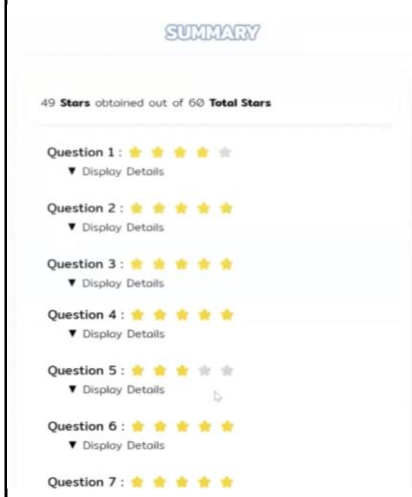
Appendix A: Screenshots of the Estimation Game Developed for this Study

Students are prompted to estimate a climate change number	True value pops up with accuracy feedback & number line & sources	Summary screen after Estimating 12 Quantities
		

Note. See ianthacker.com/design.html for details.