



Which Way Does Time Go? Differences in Expert and Novice Representations of Temporal Information at Extreme Scales Interferes with Novice Understanding of Graphs

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Abstract

Visual representations of data are widely used for communication and understanding, particularly in science, technology, engineering, and mathematics (STEM). However, despite their importance, many people have difficulty understanding data-based visualizations. This work presents a series of three studies that examine how understanding time-based Earth-science data visualizations are influenced by scale and the different directions time can be represented (e.g., the Geologic Time Scale represents time moving from bottom-to-top, whereas many calendars represent time moving left-to-right). In Study 1, 316 visualizations from two top scholarly geoscience journals were analyzed for how time was represented. These expert-made graphs represented time in a range of ways, with smaller timescales more likely to be represented as moving left-to-right and larger scales more likely to be represented in other directions. In Study 2, 47 STEM novices were recruited from an undergraduate psychology experiment pool and asked to construct four separate graphs representing change over two scales of time (Earth's history or a single day) and two phenomena (temperature or sea level). Novices overwhelmingly represented time moving from left-to-right, regardless of scale. In Study 3, 40 STEM novices were shown expert-made graphs where the direction of time varied. Novices had difficulty interpreting the expert-made graphs when time was represented moving in directions other than left-to-right. The study highlights the importance of considering representations of time and scale in STEM education and offers insights into how experts and novices approach visualizations. The findings inform the development of educational resources and strategies to improve students' understanding of scientific concepts where time and space are intrinsically related.

Keywords Graphicacy · Large-scale data · Size and scale · Temporal reasoning · Geologic time · Time representation

The world has become an increasingly information-rich environment driven by the rise of “big data,” which has led to a shift in the way we study and understand the world around us. This shift includes changes in the way information is communicated, from being primarily written symbols (language)

to a range of multimodal representations including images, videos, graphs, diagrams, maps, tables, and timelines (Heer et al., 2010). People living in the twenty-first century are more likely to encounter data visualizations in advertising (Tal & Wansink, 2014), media (The Data Visualization Society, 2021), education (Butcher, 2006; Fingeret, 2012), and assessments (Lowrie & Diezmann, 2009) than in the past. Large-scale data-based graphics are increasingly used to communicate information for individuals (e.g., weather maps and charts, political polls), the workforce (e.g., market projections, revenue), and communities (e.g., climate change, health data; Engebretsen & Kennedy, 2020). Data visualizations are also important tools for the communication and understanding of data in science, technology, engineering, and mathematics (STEM), because they help with creating meaning, reasoning, and problem solving (Abrahamsen & Bechtel, 2015; Gates, 2018; Larkin & Simon, 1987; Tversky,

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2011). Graphicacy, or the ability to understand information in the form of diagrams, graphs, and tables, is a necessary skill for the twenty-first century (Glazer, 2011; Wilmot, 1999).

Unfortunately, many people have difficulty interpreting and comprehending data-based visualizations. There is a rich literature detailing common misconceptions and barriers to developing graphicacy (e.g., McDermott et al., 1987; Planinic et al., 2012; Susac et al., 2018; Wright et al., 2017). Reviews of graphicacy literature (Glazer, 2011; Shah & Hoeffner, 2002) identify aspects of visual characteristics of the graph, prior knowledge about graph conventions, and prior content knowledge as key factors in understanding.

The current study focuses on two aspects of graphicacy that has thus far not been examined: how the representation of time at different scales (from human experience to scientific magnitudes, e.g., tens of years versus millions of years) and in different directions (e.g., along the x-axis versus the y-axis) influences understanding. This research is important because data-based visualizations frequently depict time on one axis to convey information about change over time, and important natural and social processes are often most evident at scales outside of direct human experience. For example, climate change, population growth, and pandemics all take place over time scales outside of direct human perception. Furthermore, there are discipline specific conventions for the directionality of time in visualizations (Bechtel et al., 2014), which may not be intuitive for all novice graph readers.

Understanding Time at Scales Outside of Direct Experience

Many important concepts require an understanding of spatial scales, both large (e.g., expanding universe) and small (e.g., nanotechnology), as well as non-spatial scales (e.g., government budgets and “big-data” sample sizes). Specific to time, a foundational scientific concept is the time scale of geologic structures and processes. The concept of geologic time underpins a range of scientific fields including, geology, cosmology, evolutionary biology, and ecology. As such, scale is a fundamental and unifying theme in science education (American Association for the Advancement of Science, 1993; National Research Council, 2012) and is critical for being a scientifically literate consumer of information (Tretter et al., 2006).

Unfortunately, individuals consistently have difficulty comprehending phenomena occurring at extreme scales (e.g., Delgado et al., 2007; Libarkin et al., 2007; Swarat et al., 2011; Tretter et al., 2006). For example, while students can correctly interpret the order of events that occurred during the formation of the earth, they have difficulty reasoning about the vast periods of time between these events (Libarkin et al., 2007). Estimations can be off on the order of billions

of years (Catley & Novick, 2009; Resnick et al., 2012), which can impair the understanding of related processes.

Here, we focus on temporal scales, specifically scales longer than humans can directly experience (e.g., phenomena that require thousands, millions, or even billions of years to occur). Both experts and novices learn about phenomena at different temporal scales in the same way: by analogically mapping new temporal scales (outside of direct human experience) with more familiar human ones such as spatial scales or number lines (Landy et al., 2014; Resnick et al., 2017a, b). Differences in expert and novice understanding of temporal scales may therefore be driven by increased opportunities for the experts to compare differences in the way phenomena behave at different scales (Resnick et al., 2017a). For example, sea level changes over short-term versus long-term periods of time tell us something about tides versus climate change, respectively. As experts populate their mental timelines at different scales, they may also develop a mental number line that can be more flexibly structured (Resnick et al., 2017a).

Understanding Time Represented in Different Directions

Different cultures represent temporal sequences in culturally specific ways (Bergen & Chan Lau, 2012; Boroditsky & Gaby, 2010; Göbel et al., 2011; Zebian, 2005), which appear somewhat inflexible (Holmes & Lourenco, 2011). For example, English speakers tend to arrange temporal sequences from *left-to-right*, whereas Hebrew speakers tend to arrange temporal sequences *right-to-left* (Fuhrman & Boroditsky, 2010). Even when primed to arrange temporal sequences in other directions, participants tend to demonstrate a preference for their culturally specific horizontal number line orientation (Holmes & Lourenco, 2011). This spatial numeric association of response codes (or “SNARC” effect) has been extensively explored in literature around cognitive representations (see Wood et al., 2008 for a meta-analysis of more than 100 research articles).

Aligned with different cultures having specific ways of representing temporal information, different disciplines also have different discipline-specific conventions (Bechtel et al., 2014). For example, the Geologic Time Scale is represented vertically, *bottom-to-top*, as defined by the International Commission on Stratigraphy on the International Chronostratigraphic Chart (Cohen et al., 2022). This chart is a visual representation of the history of Earth, with the Hadean Eon (~4.6 billion years ago) at the bottom and present day at the top. This representation reflects the law of superposition, a foundational principle in the geological sciences, which states that within a sequence of layers of rock, the oldest layer is at the bottom.

The principle reflects depositional processes that compile the record of past events in rocks that can be used by geologists to infer the nature of an Earth no one was around to directly observe. For a geologist, down is often older, but the orientation of rocks can change due to tectonic movement. Geologists are required to use observable spatial patterns to determine the sequence of geologic events that took place outside of direct experience (Resnick et al., 2012), a logic in the field referred to as “space-for-time reasoning” (for review, see Damgaard, 2019). For example, in sequence stratigraphy at boundaries between land and ocean, the temporal sequence of sea level changes can be inferred from horizontal patterns of rocks formed from near shore versus deep water sediment types.

In contrast to the vertical Geologic Time Scale, an initial survey found visual representations of other Earth phenomena represented in a range of different ways. For example, representations of sea level changes have expressed time as moving from *left-to-right* (Müller et al., 2008), *right-to-left* (Hallam et al., 1988), and *bottom-to-top* (Haq & Schutter, 2008; Müller et al., 2008).

The variants of this expert sea-level example suggest that subject matter experts may have developed a degree of mental flexibility with representations of time not shared by the general population (Holmes & Lourenco, 2011). Indeed, a study of expert mathematicians found a reduced SNARC effect (Cipora et al., 2016), which can be explained by a more flexible spatial-numeric representation. Experts tend to use flexible methods of representation, called “representational competence,” which enables them to solve more sophisticated problems using graphs than novices (Kozma & Russell, 1997). We are not aware of any research that examines variations in discipline-specific conventions of representing temporal information.

A corollary to expert predictions is that those with minimal experience of variations of space and time (i.e., novices) may have difficulty understanding expert-made graphs when temporal information is not aligned with their culturally specific orientation. This may reflect a relative inflexibility in relation to representations of time (Ishihara et al., 2008) or an over-familiarity with culturally specific time representations on graphs (Lowrie & Diezmann, 2009). Over-familiarity with aspects of graphs can influence the attention given to the relevant information within the graphic, and the reader’s subsequent interpretive success (Lowrie & Diezmann, 2009). Novices likely have more experience with representations of time moving in directions aligned with their cultural norms compared with discipline-specific graphs, and thus, they may misinterpret temporal information when it is not aligned with their expectations (Shah, 1995). Importantly, expert-made graphs tend to be more effective and subsequently more useful for interpretation than those constructed by non-experts (Glazer, 2011), highlighting a need to support student’s understanding of expert-made graphs.

Current Study

The current work is comprised of three studies, together aiming to inform STEM education around visualizations that involve time and scale. Our research aim in Study 1 was to characterize how expert geoscientists represent different scales of time. Geoscience is an observational science (e.g., astronomy and epidemiology) that includes all fields of natural science (e.g., physical, chemical, and biological) related to the planet Earth and planetary science. Subsequently, geoscience integrates many STEM disciplines and discoveries. We chose expert geoscientists because they frequently need to represent different scales of time when communicating about Earth processes (recall that time and scale are a unifying theme across STEM). To access expert representation, we have examined the graphs they have published in their scholarly work. We hypothesize that the representation of time may vary by scale, with phenomena at geologic scales aligned with an expert’s experience with superposition and the vertical positioning of the Geologic Time Scale, and phenomena at human scales aligned with the experience of the typical calendar representation in the country where the journal is published.

Our research aim in Study 2 was to characterize how novices represented time, and whether choice of orientation was influenced by scale. We hypothesize that, because geoscience novice’s likely have limited experience with the geologic time scale, there will be no differences in how they represent time across different scales of time. Instead, we anticipate novices to always represent time aligned with their culture’s writing direction, which in this study is left-to-right.

Having found a difference between how experts and novices represent time at scales outside of human experience, in Study 3, our research question was to examine how orientation of time influenced novices’ ability to correctly interpret time represented on expert-made graphs. That is, can novices understand expert-made graphs when time is not aligned with their typical representation? These findings are important because novices are often required to interpret expert-made graphs both in STEM education and in daily life (see review above).

Study 1: Expert-Made Graph Methods

Participants

The sample consisted of every table and figure ($n = 852$) printed in the *Journal of Geology* and *Geology* in a single publication year (2011). These journals were chosen because they have the highest impact factors for journals in the field of geoscience (3.04 and 3.89, respectively) and are intended for a broad geoscience audience. Although the *Journal of*

Metamorphic Geology has a higher impact factor than *Journal of Geology*, it is focused on the subfield of metamorphic studies, so it was not included in the analysis.

Data Analytic Procedure

The tables and figures were coded as either containing temporal information ($n = 536$) or not including temporal information ($n = 316$). Only the tables and figures that included temporal information were included in further analysis. These temporal tables and graphs were coded for the direction time was represented: progressing left-to-right, right-to-left, top-to-bottom, bottom-to-top, or no single dimension (see Fig. 1). They were also coded for type (table, graph, map, or illustration) and for scale of time (less than 1 year, tens of years, hundreds of years, thousands of years, millions of years, billions of years).

Study 1: Expert-Made Graph Results

The results from the analysis of the expert-made graphs found in the *Journal of Geology* and *Geology* show that the most frequently adopted convention for representing the direction of time (from the past to the present), at all magnitudes and scales, was *right-to-left*, equating to 54.79% of all printed tables and figures (Table 2). The least-adopted convention for representing time was *top-to-bottom*, equating to 8.47% of all printed tables and figures. Although all orientations were used across a range of different scales, ranging in magnitude from “less than 1 year” to “billions of years,” there was an effect of scale in their relative frequency. Graphs representing time as *right-to-left*, *bottom-to-top*, or *top-to-bottom* were more likely to be at scales of thousands of years or more. An opposite trend is seen for graphs representing time as *left-to-right*, which are more

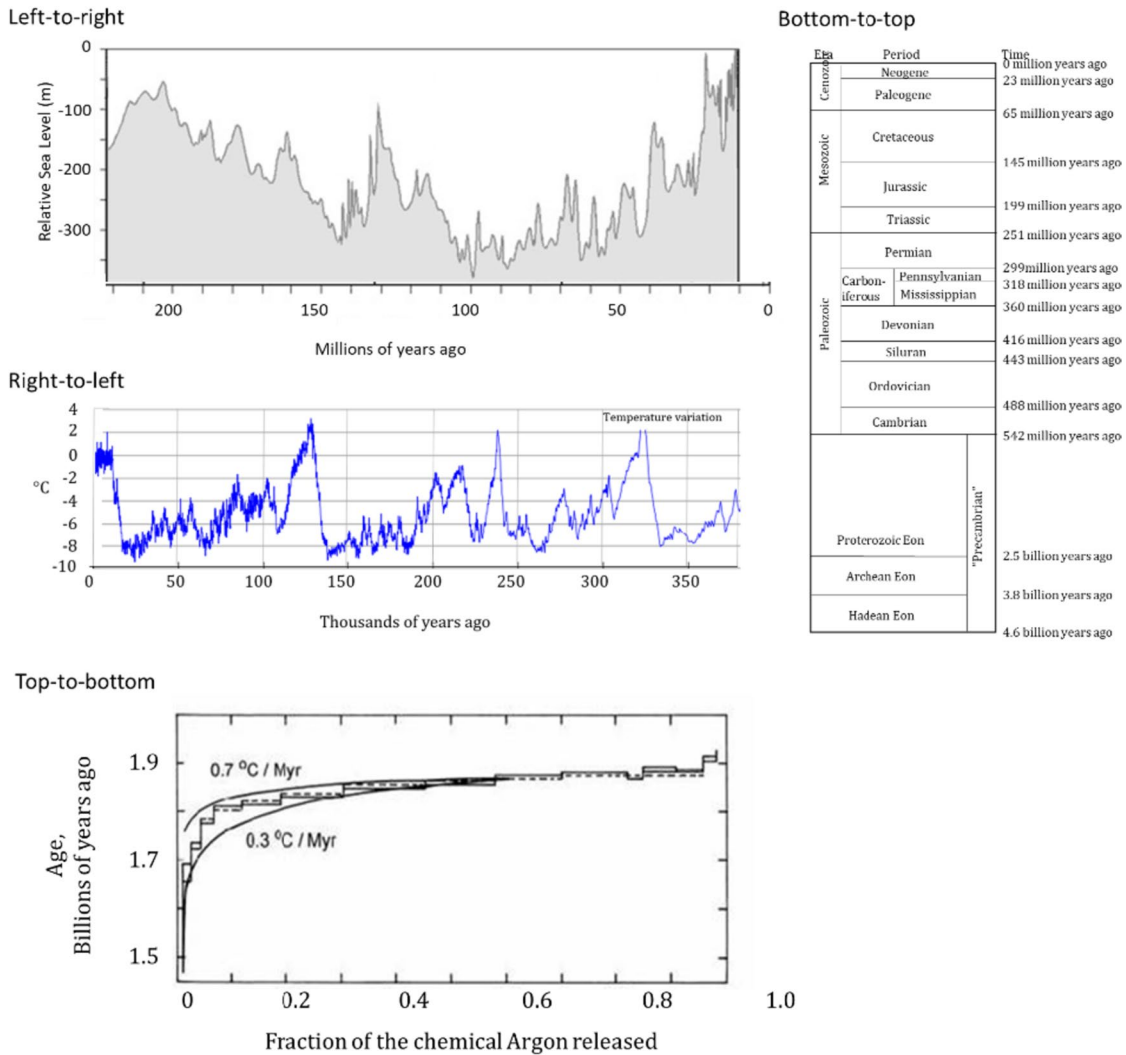


Fig. 1 Example graphs taken from *Journal of Geology* and *Geology* showing how direction of time can be represented

likely to be at scales of hundreds of years or less. A chi-square test ($\chi^2(1, 3) = 32.001, p < .001$) confirmed the readily apparent differences in between visualizations at human time scales and geological time scales shown in Table 1.

Study 2: Novice-Made Graph Methods

Participants

Participants ($n = 48$; 17 male, 30 female, 1 not reported) were recruited from an undergraduate psychology experiment pool at a large urban American university in exchange for course credit. The study contained 59% of participants identifying as “Caucasian,” 7% identifying as “Asian,” 19% identifying as “African American,” and 15% identifying as “other” (and one participant not reporting their ethnicity). Education levels include 23% freshman, 27% sophomore, 29% junior, 6% senior, and 15% who simply identified themselves as “college level” or an “undergraduate student.” Fifty percent of students had previously taken a geoscience course in high school or college.

Procedure

Participants were asked to construct four separate graphs: Earth’s history of temperature change, a single day of temperature change, Earth’s history of sea level change, and a single day of sea level change. Participants constructed each graph one at a time in a randomized order (see Fig. 2 for examples of novice-made graphs). After completing each graph, if time was not labeled the experimenter would say, “As with any graph, please be sure to label all the graph’s parts. If you used a bar graph you should label what the bar represents, if you used a line graph you should label what the line represents, and so on. You should also label the title of the graph and the axes. Please do this now.” If the participants did not label time in this step, the experimenter would ask if time was represented in the graph, and if so, they would ask the participant to label “how much time has passed by labeling the ends of where time is represented.”

Table 1 Percentage of different temporal representations of expert-made graphs from analysis of all tables and figures from *Journal of Geology and Geology*

Time scales	Orientation of temporal representation (%)			
	Left-to-right	Right-to-left	Bottom-to-top	Top-to-bottom
Less than 1 year	2.26	0.28	0.85	1.13
Tens of years	5.08	0.28	-	0.28
Hundreds of years	1.41	-	-	-
Thousands of years	5.93	22.60	6.50	1.98
Millions of years	5.93	31.35	8.47	4.80
Billions of years	-	0.28	0.28	0.28
Total %	20.36	54.79	16.10	8.47

Study 2: Novice-Made Graph Results

Participants were significantly more likely to represent time as moving *left-to-right* across scale and content, Earth history of temperature change: $\chi^2(3, 48) = 93.50, p < .001$, Earth history of sea level change: $\chi^2(3, 48) = 100.17, p < .001$, single day of temperature change: $\chi^2(3, 48) = 100.17, p < .001$, single day of sea level change: $\chi^2(3, 48) = 81.17, p < .001$. No participants used a *right-to-left* temporal representation. There were six students who consistently used a *bottom-to-top* or *top-to-bottom* temporal representation for at least one graph. Three participants represented time as moving from *bottom-to-top* for all four graphs, and one participant did so for three of the four graphs. One student represented time as moving from *top-to-bottom* for three of the four graphs, and one student did so for one of the four graphs. For the three students who represented a portion of their graphs as *bottom-to-top* or *top-to-bottom*, all their other graphs represented time as *left-to-right*. Two participants did not label or represent time for three of the four graphs, one participant did not for two of the four graphs, and one participant did not for one of the four graphs. See Table 2 for distribution of response frequencies.

Study 3: Novice-Interpreted Graph Methods

Participants

Participants ($n = 40$; 15 male and 25 female) were recruited from the same undergraduate psychology experiment pool as in Study 2. The study contained 57% of participants identifying as “Caucasian,” 10% identifying as “Asian,” 20% identifying as “African American,” and 13% identifying as “other.” Education levels include 25% freshman, 35% sophomore, 32% junior, and 8% senior. Slightly less than half of the participants (48%) had previously taken a geoscience course in high school or college.

Materials

From the sample of expert-made graphs in Study 1, one graph was identified that represented time moving from each

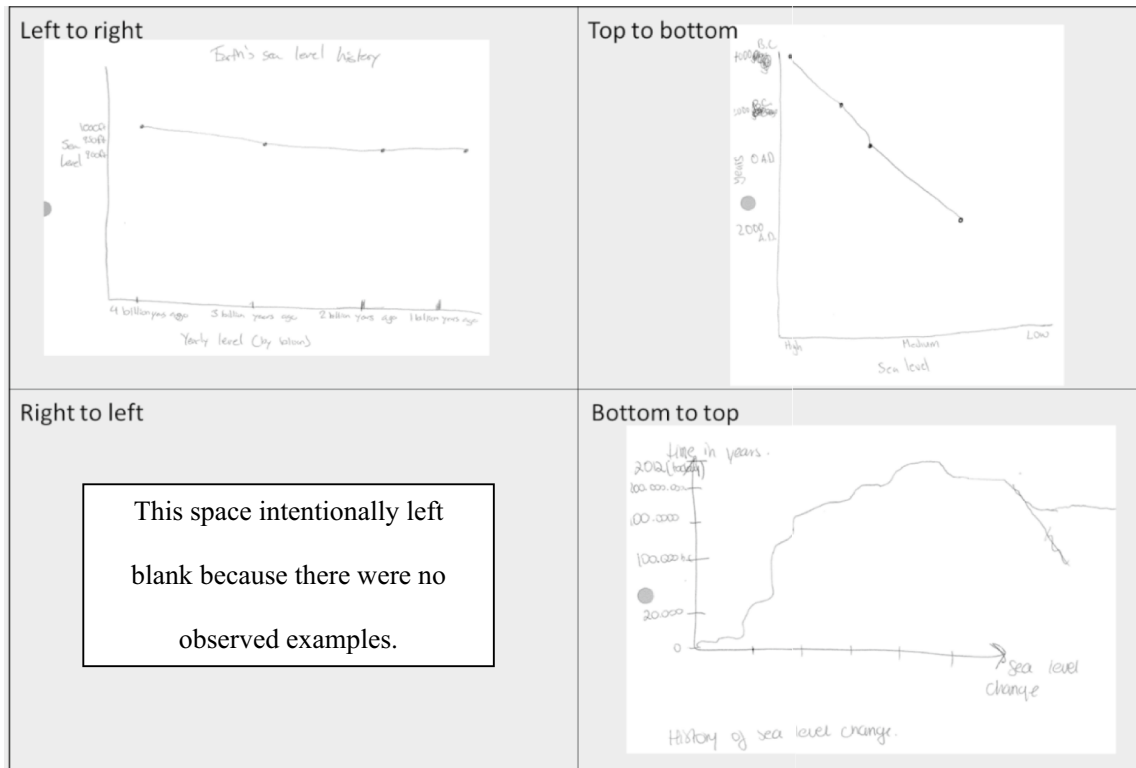


Fig. 2 Examples of novice-made graphs for each type of temporal representation: left-to-right, right-to-left, top-to-bottom, and bottom-to-top

of the four observed categories: *left-to-right*, *right-to-left*, *bottom-to-top*, and *top-to-bottom* (see Fig. 1 from Study 1). These four “base” graphs also presented different content: *left-to-right* = temperature, *right-to-left* = sea level, *top-to-bottom* = argon, and *bottom-to-top* = the Geologic Time Scale. We purposefully chose the Geologic Time Scale as the bottom-to-top representation because the categories are foundational to learning and students would be required to understand this for introductory geoscience classes. A pool of graphs was created by modifying the four expert-made base graphs so that the new set of graphs represented time in each of the four directions (see Fig. 3). This resulted in 16 total graphs (four base graphs × four directions). All other features of the graph were held constant.

Measures

Participants were asked four multiple-choice questions for each graph. Two of these questions were dependent on understanding the direction time was represented. In the example provided (see Fig. 4), a portion of the graph is circled showing sea level changing over time. Participants are asked to identify if the sea level is increasing, decreasing, staying the same, or if this graph does not measure sea level change. If the participant understood that time is moving from right-to-left, they would correctly identify that sea level is *decreasing*; however, if they incorrectly believed that time was represented as moving left-to-right, they would incorrectly identify that sea level was *increasing*. The other two

Table 2 Distribution of participants’ temporal representations (rows) of change over time. Participants created graphs representing changes to (1) sea-level and (2) temperature over the course of (1) Earth’s history or (2) a single day (columns)

Orientation of temporal representation	Participants’ representations of change over time (%)			
	Sea level Earth’s history	Temperature Earth’s history	Sea level single day	Temperature single day
Left-to-right	84	86	86	92
Right-to-left	0	0	0	0
Bottom-to-top	8	8	8	4
Top-to-bottom	4	2	4	2
Other	4	4	2	2

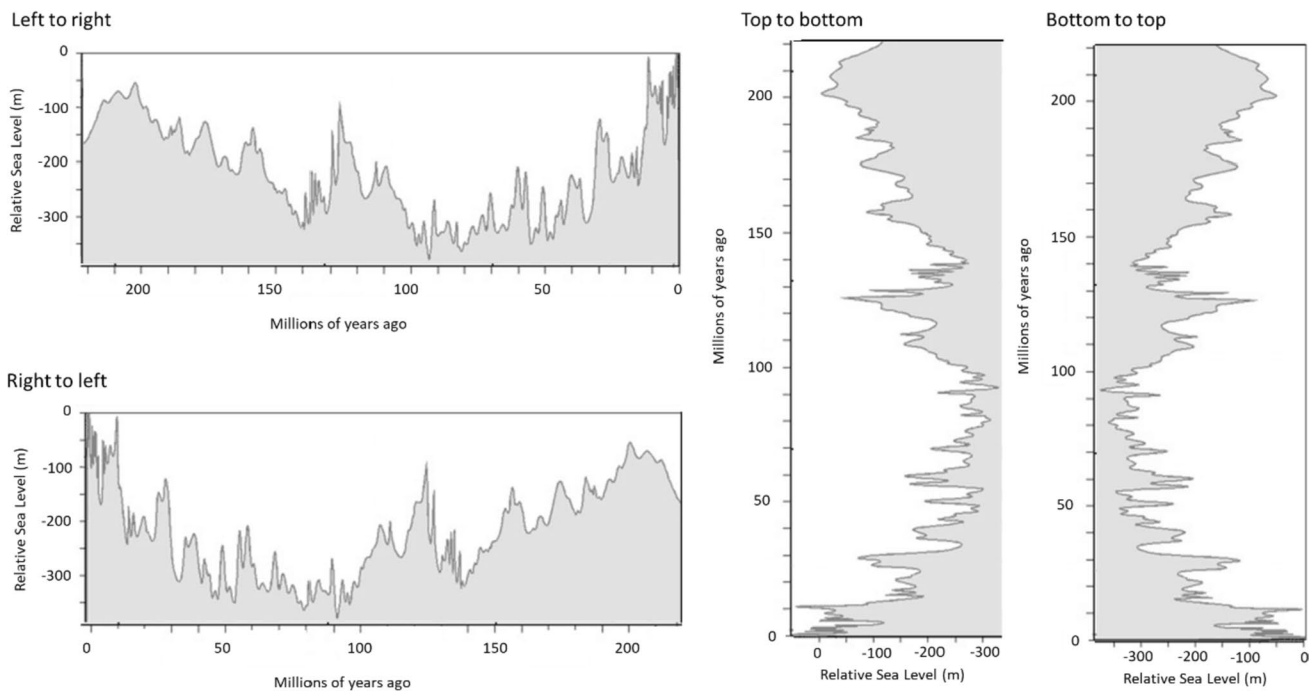


Fig. 3 Example of an expert-made graph, which was modified to show time represented as moving in four different directions. In this example, time was originally represented as moving from right-to-left

questions were fact-based and did not require understanding time. For example, participants were asked to identify the sea level at a given point (indicated by an arrow). Participants were assigned one point for each correct response for each of the four graphs that represent time moving in different directions.

Procedure

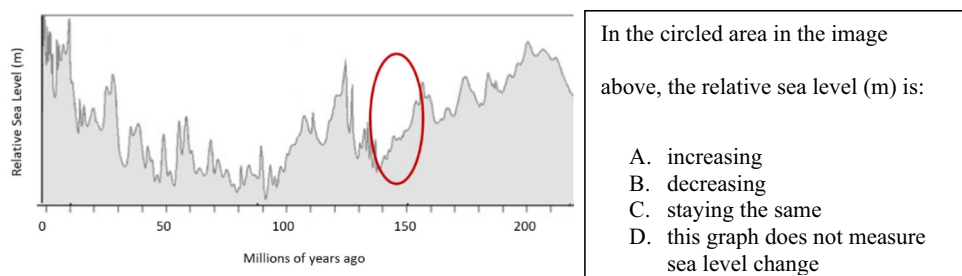
Participants were presented with one graph in the center of a computer screen and had an unlimited amount of time to read and understand the graph. When ready, the participants pressed any button to begin answering the questions. The graph remained on the screen the whole time for reference. Participants answered one question at a time and could not go back. Question order was randomized. Content and direction were quasi-randomized, such that the first graph shown was pulled at random from the 16 graphs, and then

all other graphs that had the same content or same direction were removed so that the second graph was randomly pulled from the remaining nine graphs, and same for the third graph (pool of four remaining graphs), and fourth graph (only one remaining graph).

Study 3: Novice-Interpreted Graph Results

A repeated measures analysis of variance was conducted to examine if the direction of time within a graph representation influences performance on time-based and fact-based questions. There was a significant effect for time-based questions, $F(1, 38) = 206.571, p < .0001$, but not fact-based questions, $F(1, 38) = 1.67, p = .177$. Six paired sample *t* tests (corrected using a Bonferroni correction for multiple comparisons) were used to make post hoc comparisons between the conditions for time-based items. Participants’ responses for time-based questions were significantly more

Fig. 4 Example of time-based question



accurate when time was represented left-to-right compared to any other format, $t's(3) = 3.89$ to 5.75 , $p's < .001$. There were no differences between performance on time-based questions across other formats, $t's(3) = .279$ to 1.33 , $p's = .09$ to $.78$. See Table 3 for the percentage of participants with correct responses for time-based vs. fact-based questions for each direction time represented.

Discussion

The results from this study show that expert-made graphs represent time in different orientations, and that the choice of representation is influenced by scale. Relatively smaller scales (less than a year, tens, or hundreds of years) tend to be represented from *left-to-right*, whereas as relatively larger scales (thousands, millions, or billions of years) tend to be represented in other orientations, especially *right-to-left*. In contrast, novices represent time in only one way—*left-to-right*—regardless of scale and have difficulty interpreting expert-made graphs when time is oriented in any direction other than *left-to-right*.

The novice representations of time in this study are aligned with mainstream graph conventions for graph construction. There are many established graph conventions that facilitate data interpretation (Peng et al., 2017). Mainstream conventions in Western cultures explicitly recommend representing time as moving *left-to-right* along the horizontal axis, the dependent variable along the vertical axis, and the vertical axis on the left-hand side of the graph (Fung, 2020; Prime Education, 2019; Velez, 2020).

A *left-to-right* preference within Western cultures is consistent with the spatial numeric association of response codes (SNARC) effect (Dehaene et al., 1993; Vallesi et al., 2008), where magnitude is cognitively represented with small values on the left and larger values on the right. The interrelatedness of human cognition of numbers, space, and time has been comprehensively explored in the research literature and is thought to have an ancient evolutionary origin in the brain's parietal cortex to support our interactions with the external world (Cohen Kadosh et al., 2008; Skagerlund et al., 2016; Winter et al., 2015).

The expert-made graphs in this study varied from the mainstream *left-to-right* convention at relatively larger scales. This may reflect that experts have access to alternative conventions specific to their field based on characteristics of phenomena at extreme scales. For example, and as noted previously, the Geologic Time Scale (which represents time as *bottom-to-top*) follows the law of superposition, where the oldest rock is at the bottom and newer rock forms increasingly on top. In geology, horizontal, linear scales are useful for comparing relative ages of rock layers and any associated changes over time (see for example Van Hinte, 1978).

Expert conventions may also intersect with mainstream Western conventions in different ways. This may explain why the most common expert-made graph represented time oriented from *right-to-left*. Properties of Cartesian planes set zero (present day) in the middle of increasingly larger negative numbers (e.g., the past) moving toward the left and positive numbers moving toward the right (e.g., the future); however, mainstream conventions require the y-axis to be positioned on the left-hand side. If present day remains on the y-axis, this inverts the direction of time to a *right-to-left* orientation.

The range of temporal representation observed in expert-made graphs suggests some amount of cognitive flexibility in experts to reason about time moving in different orientations. When estimating location, geoscientists are able to flexibly shift their perceptual frame of reference between novice- (e.g., between two trees) and expert (e.g., it is near a fault line)-defined categories based on which is more accurate (Holden et al., 2016). Although the SNARC effect is relatively stable based on writing direction (Holmes & Lourenco, 2011), individuals who are bilingual are also able to access different representations of magnitude depending on the linguistic context (Shaki & Fischer, 2008). It may be the case that expert scientists hold varying representations dependent on scale and phenomena and apply these representations flexibly based on task demands. Future research is required to characterize expert's cognitive representations of magnitude, which might examine if experts have a single mental number line that is flexibly structured or separate mental number lines for different scales and phenomena.

Educational Implications

Understanding and representing time at all scales is an essential skill that helps students make connections between events or phenomena and improve critical thinking in real-world applications. The ability to describe, measure, and represent both small and large units of time is explicitly included in national school curricula (e.g., Australian Curriculum, 2023) as well as having been identified as a unifying theme in science education (American Association for the Advancement of Science, 1993; National Research Council, 2012). A key concept emphasizes the importance

Table 3 Percentage of correct participant responses for time-based questions compared to fact-based questions

Orientation of temporal representation	Correct participant responses (%)	
	Time-based	Fact-based
Left-to-right	82.5	82.5
Right-to-left	37.5	82.5
Top-to-bottom	50	83.75
Bottom-to-top	53.75	83.75

for students to be able to understand that natural processes occur over a range of scales, from millions of years to nano-seconds. Therefore, it is crucial that students learn to correctly interpret and create graphical representations of time.

Unfortunately, the results from Study 3 show that novices have difficulty interpreting time moving in directions other than *left-to-right*, which is how the majority of expert-made graphs are represented at larger scales (Study 1). There are several explanations for why most novices struggled, including cognitive processing, understanding conventions, missing important details, and complex interactions between learner and diagram characteristics and task demands (for review, see Cromley et al., 2013). We consider these below with respect to the representation of time in different directions and at different scales.

Representation of Time in Different Directions

Recall that novices represented time from *left-to-right* in Study 2 and, in Study 3, got questions correct when time was represented *left-to-right* and wrong when time was represented in other directions. Together, this could suggest that novices are using a *left-to-right* convention, which is applied (and misapplied) uniformly across all graphs. Because of their over-familiarity with left-to-right representations of time, novices may fail to notice if time is represented in another way (Lowrie & Diezmann, 2009) or fail to use the labeled axes (Cromley et al., 2010).

If the main barrier to graph comprehension is understanding conventions, then students may benefit from explicit convention instruction (Cromley et al., 2013). Undergraduate students consistently demonstrate low levels of diagram comprehension (e.g., Scheiter et al., 2009), which can be explained by a lack basic pre-requisite convention knowledge. Cromley et al. (2013) found that students who are taught conventions of diagrams have larger gains in understanding diagrams compared to those receiving regular instruction.

Notably, experts may have developed different conventions for representing different phenomena at different scales because it reflects key attributes of those phenomena. Therefore, highlighting the relationship between experience and representation might be a pathway for students to develop a better understanding of both. For example, the superposition of rocks during deposition (the experience) as measured by core samples (the tool) may inform how these timescales are visually represented (the representation), which illustrates how experts' understanding of scale is connected to the tools they use to measure it. There may be a role for tools in the development of students' ability to understand and interpret representations.

Alternatively, it is possible that a novice's difficulty understanding graphs with time represented in directions other than *left-to-right* is due to cognitive inflexibility. Aligned with this interpretation, Holmes and Lourenco (2011) found that an individual's internal spatial representation of magnitude was

fairly inflexible. If this were the case, students may require repeated exposure and repetition of engaging with graphs showing time represented in different ways to help overcome their automated response (Cañas et al., 2003).

Representation of Time at Different Scales

Conceptualizing and applying a scale is challenging. To understand a scale requires an understanding of a range of linear and non-linear measurement concepts, such as quantity, distance, proportion, temperature, time, volume, and mass (Jones & Taylor, 2008; Resnick et al., 2017a, b). In addition, scaling ability requires measurement coding and an understanding of how that measurement corresponds to the real world (Huttenlocher et al., 1999). When reasoning about geologic time, however, novices rely on spatial reasoning methods based on conventional time, which are insufficient and result in misconceptions (Cheek, 2013).

Relational reasoning is one strategy that may be used to bridge understanding between time conceptualized at a human scale versus geologic time spanning billions of years. Relational reasoning requires the identification of similarities and differences between different mental representations (e.g., distance, time), which are then applied logically in novel or unfamiliar situations to solve problems (e.g., geologic time scales). Resnick et al., 2017a, b) developed a theoretical framework of how relational reasoning can support students' reasoning about scale and employs the use of representational tools, such as body rulers and anchor points, between human scales and the unfamiliar scale. It may also be necessary to make a series of analogic steps, moving from smaller more familiar scales to increasingly larger less familiar scales (Resnick et al., 2017a).

Limitations and Future Directions

The current study captured experts' representation of time via published graphs, which limits our ability to make inferences around cognitive/mental representations. We tried to balance this within the manuscript through consideration of conventions and cognitive representations. Future research should characterize expert and novice representations of time and scale, including experts from a range of STEM fields and a range of temporal magnitudes (e.g., smaller than humans can directly experience). Such research may examine the role of context in forming mental representations of magnitude. For example, how is direction of time meaningful to the phenomena and scale, and do experts possess separate mental number lines for different contexts (phenomena) or a single mental number line that can be flexibly applied? This would have implications for cognitive research on abstract number line development, which contrast wholistic (Siegler

& Lortie-Forgues, 2014) versus segmented (Ebersbach et al., 2008) models.

Future research should also consider the best educational practices when teaching about phenomena at larger scales and the graphs used to represent them. Such work could experimentally assess the impact of explicit instruction on diagram conventions, as well as using representations of time in a range of directions. Students can have difficulty aligning multiple representations (Resnick et al., 2017a, b), however, and so, interventions using multiple representations of time should take care to ensure alignment.

Conclusions

Expert-made graphs tend to be more effective and subsequently useful for interpretation (Glazer, 2011). In the case of representing time across scale, the current study found that experts utilize a range of different directions. Unfortunately, we also found that novices have difficulty constructing and interpreting graphs that do not represent time as moving from *left-to-right*. Given the importance of understanding graphs, and the cross-cutting role of scale in STEM, educators and school-based curricula should consider the most effective pedagogical strategies for teaching novices (students) how to understand and work with time scales, as well as the appropriate timing of this content in the curriculum scope and sequence.

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Author Contribution I.R. and T. F. S. conceptualized the research questions and designed the methodology for the three studies. I. R. collected the data and analyzed the results. I. R. and E. L. C. positioned the findings within the broader literature and were major contributors in writing the manuscript. All authors read, edited, and approved the final manuscript.

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Availability of Data and Materials The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethical Approval Ethical approval was obtained from Temple University's Internal Review Board to conduct the studies described in this manuscript.

Informed Consent Research Involving Human Participants and/or Animals No personally identifying information is included in this manu-

script. All data is anonymous and aggregated at the group level for analysis. There is no description of individual participants.

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

Consent for Publication The authors affirm that human research participants provided informed consent for publication.

Competing Interests The authors declare no competing interests.

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