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Adults Systematically Underestimate Decimals and Whole Number Exposure Induces Further Magnitude-Based Underestimation

Lauren K. Schiller[1, 2, 3], Roberto A. Abreu-Mendoza[1], and Miriam Rosenberg-Lee[1]
[1] Department of Psychology, Rutgers University
[2] Teachers College, Columbia University
[3] Department of Psychological Sciences, Kent State University

Decimal numbers are generally assumed to be a straightforward extension of the base-ten system for whole numbers given their shared place value structure. However, in decimal notation, unlike whole numbers, the same magnitude can be expressed in multiple ways (e.g., 0.8, 0.80, 0.800, etc.). Here, we used a number line task with carefully selected stimuli to investigate how equivalent decimals (e.g., 0.8 and 0.80 on a 0–1 number line) and proportionally equivalent whole numbers (e.g., 80 on a 0–100 number line) are estimated. We find that young adults ($n = 88$, $M_{age} = 20.22$ years, $SD = 1.65$, 57 female) have a linear response pattern for both decimals and whole numbers, but those double-digit decimals (e.g., 0.08, 0.82, 0.80) are systematically underestimated relative to proportionally equivalent whole numbers (e.g., 8, 82, 80). Moreover, decimal string length worsens the underestimation, such that single-digit decimals (e.g., 0.8) are perceived as smaller than their equivalent double-digit decimals (e.g., 0.80). Finally, we find that exposing participants to whole number stimuli before decimal stimuli induces magnitude-based underestimation, that is, greater underestimation for larger decimals. Together, these results suggest a small but persistent underestimation bias for decimals less than one, and further that decimal magnitude estimation is fragile and subject to greater underestimation when exposed to whole numbers.

Keywords: Decimal magnitude understanding, number line estimation, logarithmic vs. linear magnitude estimation, whole number priming

For decades, research in numerical cognition has focused on whole numbers (Booth & Siegler, 2006; Dehaene et al., 1993; Macizo & Herrera, 2010, 2013; Moeller et al., 2011, 2013; Moyer & Landauer, 1967; Nuerk et al., 2001, 2004; Nuerk & Willmes, 2005; Opfer & Siegler, 2007; Siegler & Booth, 2004). More recently, rational numbers have come into the spotlight, driven by the persistent difficulties learners have with these critical numbers and their practical importance. For example, approximately two-thirds of white- and blue-collar workers report using fractions, decimals, and percentages daily (Handel, 2016). Yet, many people struggle with rational numbers, leading to real-world consequences. In fact, diabetes outcomes (Cavanaugh et al., 2008) and even mortgage default rates (Gerardi et al., 2013) are predicted by rational number proficiency (Rosenberg-Lee, 2021).

Thus far, investigations of magnitude representations have concentrated primarily on understanding whole numbers and, somewhat on fractions, with little attention to decimals. Decimal numbers are generally assumed to be a straightforward extension of the base-ten system for whole numbers given their shared place value structure. However, a crucial difference between decimals and whole numbers is that longer digit trains signify larger magnitudes for whole numbers but not always for decimals. Individuals are thought to represent numbers on a mental number line (Dehaene et al., 1993; Moyer & Landauer, 1967; Siegler et al., 2011), with adults estimating the positions of whole numbers linearly, while children's estimations tend to be logarithmic (Booth & Siegler, 2006; Opfer & Siegler, 2007; Siegler & Booth, 2004). While recent work suggests fractions are also estimated linearly (Iuculano & Butterworth, 2011; Siegler et al., 2011), much less is known about the decimal estimation patterns, especially when taking into account that the same decimal magnitude can be expressed in different ways (0.8, 0.80, 0.800, etc.). The number of digits has been shown to affect decimal ordering (Van Hoof et al., 2018) and decimal comparison, specifically

Lauren K. Schiller https://orcid.org/0000-0002-9986-0224

In accordance with the journal's Transparency and Openness Promotion, we have made available all analyses in a html version of a R-markdown file: https://osf.io/kvbf8/?view_only=587602aa437f40be8c4b367d65d6dcf2. This file is a dynamic document based on our R code used for analyses, including the code, results, rendered output, and a brief description of analyses. Unfortunately, we are not able to share the individual data in raw form, as our IRB consent forms did not allow for public sharing of individual data. Moreover, the PsychoPy task used in the current study was part of a larger study and thus cannot be separated. However, we would be happy to share the PsychoPy task upon request with interested researchers. Finally, the study was not preregistered.

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Correspondence concerning this article should be addressed to Lauren Schiller, Department of Psychology, Rutgers University, Newark, 101 Warren St., Smith Hall Room 338, Newark, NJ 07102, United States. Email: lauren.schiller@tc.columbia.edu

performance is worse when the larger decimal has less digits (e.g., 0.9 vs. 0.23) (Coulanges et al., 2021; Desmet et al., 2010; Durkin & Rittle-Johnson, 2015; Huber et al., 2014; Roell et al., 2017, 2019; Varma & Karl, 2013). Here, we use a number line task to investigate magnitude estimation of the same proportional information to determine how performance varies by number system (whole vs. decimal) and within decimals by the number of significant digits (single- vs. double-digits).

Decimals: Log or Linear?

A common task thought to measure how individuals understand the magnitude of numbers is number line estimation (Booth & Siegler, 2006; Laski & Siegler, 2007; Opfer & Siegler, 2007; Siegler & Booth, 2004; Siegler & Opfer, 2003; Thompson & Opfer, 2008). As part of this standard task, participants are shown a number line with two labeled endpoints and asked to estimate the position of another number on the number line. Precision on both the whole number and the fraction versions of the task is correlated with whole number calculation accuracy and math achievement (Booth & Siegler, 2006, 2008; Schneider et al., 2009; Siegler & Booth, 2004; Siegler et al., 2011). Debate surrounds, whether this task taps into actual magnitude representations, or if specific response patterns (i.e., logarithmic vs. linear fits) simply reflect properties of the task and participants' knowledge (Barth et al., 2011; Barth & Paladino, 2011; Cantlon et al., 2009; D. J. Cohen & Blanc-Goldhammer, 2011). Here, we focus on comparing decimal response patterns to known performance patterns for whole numbers.

It is well established that when whole number magnitude knowledge is assessed with a number line, response patterns follow a logarithmic fit at early ages and a more linear fit (i.e., more precise) with development (for a review, see Siegler et al., 2009). Specifically, children overestimate small numbers and underestimate large numbers following a logarithmic trend (i.e., $y = k \times \ln(x)$). By contrast, adults tend to place numbers on the number line so that the positions of estimates increase linearly with the actual magnitude (i.e., $y = k \times x$). Moreover, the numerical range has an impact on whether numerical estimation fits a logarithmic or linear trend for children. For example, second-grade children exhibit a linear pattern on 0–100 number lines (Siegler & Booth, 2004) but a logarithmic pattern on 0–1,000 number lines (Opfer & Siegler, 2007). Therefore, even though the general trend involves a log-to-linear shift, children's response patterns are fragile for whole numbers based on the numerical context. In fact, adults can also be induced to show logarithmic patterns, such as when presented less familiar numerical stimuli like $0.002 \times 10^{4.5}$ (Chesney & Matthews, 2013; Landy et al., 2013, 2017) and less familiar anchors like 1,639–2,897 (Hurst et al., 2014). Thus, it is important to take caution in interpreting number line estimation as an indicator of one's internal representation of number, especially when these patterns of results are not present in other types of magnitude estimation tasks (Barth et al., 2009). Even still, the number line estimation task has proven a useful measure of mathematical understanding and is predictive of other math skills (Schneider et al., 2018; Siegler & Booth, 2004; Siegler et al., 2011, 2012).

While some work has examined fraction estimation using number lines (Booth et al., 2014; Booth & Newton, 2012; Iuculano & Butterworth, 2011; Siegler et al., 2011), less is known about whether decimals are estimated logarithmically or linearly. Several studies have examined decimal number line estimation (DeWolf et al., 2015; Ganor-Stern, 2013; Iuculano & Butterworth, 2011; Rittle-Johnson et al., 2001; Tian & Siegler, 2017); however, only one paper to date has used statistical methods to fit participants' performance. Iuculano and Butterworth (2011) tested whether adults' and children's number line estimates were better fit by a logarithmic or linear pattern for fractions, decimals, integers (positive whole numbers), and money. They report that by at least the age of 10 years, individuals demonstrated a linear pattern of response for all of the different number types. However, Iuculano and Butterworth did not systematically manipulate the number of digits presented, only reporting the full set of fraction stimuli and mentioning fraction-to-decimal translations could be exact (i.e., $1/4 = 0.25$) or approximate (i.e., $1/9 = 0.1$). This leaves open the question of whether decimals of differing lengths are all estimated linearly on a number line, given that numerous studies have demonstrated that the number of digits influences magnitude processing of decimals (Coulanges et al., 2021; Desmet et al., 2010; Durkin & Rittle-Johnson, 2015; Huber et al., 2014; Roell et al., 2017, 2019; Varma & Karl, 2013). Thus, the first aim of this study was to replicate the finding of linear representations of decimals in adults, in a well-defined stimulus set, which manipulates decimal length.

Underestimation of Decimal Magnitudes

While it is common to measure the precision of number line estimation using percent absolute error (PAE; e.g., Booth & Siegler, 2008; Hamdan & Gunderson, 2017; Rivers et al., 2021; etc.), this metric cannot distinguish between over- and underestimation. Two lines of research bear on the direction of decimal and whole number estimation.

First, there is evidence of underestimation (i.e., left bias) in general with both physical space and numbers. For example, healthy adults demonstrated a left bias in bisecting physical lines and generating a midpoint number between two given whole numbers (Longo & Lourenco, 2007). Adults are also more likely to generate smaller rather than larger numbers in random number generation tasks (Loetscher & Brugger, 2007) and they even underestimate the numerosity of dot arrays containing 1–100 dots (Izard & Dehaene, 2008). For example, participants responded "30" for numerosities ranging from 59 to 82 dots. These results predict general underestimation for both whole and decimal numbers.

Second, a separate line of research suggests decimals are perceived as smaller than their equivalent percentages (Schiller, 2020; Schiller & Siegler, 2022). For example, middle school students were, on average, more accurate on magnitude comparison trials where the decimal was smaller than the compared percentage (e.g., 0.25 vs. 40%) than the opposite (e.g., 0.40 vs. 25%). Since percentages are often discussed colloquially as whole numbers (e.g., "She earned a 100 on her test."), we might see similar effects where decimals are underestimated relative to whole numbers. Consistent with this idea, conference proceedings from Tian and Siegler (2017) demonstrated that children underestimated single-digit decimal stimuli relative to double-digit stimuli. Moreover, Jones (2017) found that decimals, especially those between 0.6 and 1, were underestimated on a number line estimation task, while fractions were not. Given the similarities between percentages and whole numbers, these results suggest that decimals should be underestimated relative to equivalent whole numbers.

Thus, in order to investigate the direction of estimation errors, we did not calculate PAE and instead computed the difference between estimates and actual values, a metric we call *directional error*. The second aim of this study was to investigate whether decimal stimuli are over- or underestimated relative to their whole number equivalents.

String Length and Magnitude Interference Effects

At first pass, decimals appear very similar to whole numbers because of their shared place value. A key phenomenon in whole number processing is distance effects, that is, worse performance for near (8 vs. 9) than far (2 vs. 9) comparisons. Several magnitude comparison studies have shown that decimal processing also displays distance effects (DeWolf et al., 2014; Ganor-Stern, 2013; Hurst & Cordes, 2016, 2018b; Kallai & Tzelgov, 2014; Wang & Siegler, 2013). Specifically, response time and accuracy for decimal comparison are worse for near (0.8 vs. 0.9) than far comparisons (0.2 vs. 0.9). Yet, many comparison studies demonstrate a phenomenon unique to decimal numbers, namely that the number of digits can interfere with decimal comparison (Coulanges et al., 2021; Desmet et al., 2010; Durkin & Rittle-Johnson, 2015; Huber et al., 2014; Roell et al., 2017, 2019; Varma & Karl, 2013). The classic demonstration of this effect is where participants are slower and less accurate when the larger decimal has a shorter digit train (e.g., 0.23 vs. 0.9). In contrast, a longer digit train always signifies larger magnitude for whole numbers (e.g., $23 > 9$) but not for decimals (e.g., $0.23 < 0.9$).

Two explanations have been posited for this effect. Huber and colleagues (2014) call it the *string length congruity effect* and propose that when decimals strings are compared there is a separate comparison for each digit (i.e., left to right) and a comparison of the physical length of the string. The interference between these independent comparisons gives rise to unit-decade compatibility effects (Nuerk et al., 2001; Nuerk, Kaufmann, et al., 2004; Nuerk, Weger, et al., 2004; Nuerk & Willmes, 2005) and string length effects. A computational model using these independent predictors well fit Huber and colleagues' (2014) experimental data.

An alternative explanation, termed the *semantic interference* effect by Varma and Karl (2013), posits that participants automatically activate the whole number referents of the decimals to be compared. Thus, the decimals 0.9 and 0.23 activate the magnitudes of the whole numbers 9 and 23, respectively, making it challenging to correctly compare these values. Notably, adding zero to previously incongruent stimuli removes this interference effect (e.g., 0.90 vs. 0.23 resulted in faster response time), suggesting that activating the appropriate magnitude ($0.90 = > 90$) resolves the interference (Coulanges et al., 2021; Varma & Karl, 2013). Further evidence that string length is not the only factor in mismatched length comparison comes from recent research in multidigit comparison which finds that both the string length and the left-digit magnitude simultaneously impact large whole number processing (García-Orza et al., 2023; Lozin & Pinhas, 2022). For example, Lozin & Pinhas (2022) found that adults take longer when comparing pairs of numbers whose left digits are incongruent with the longer string length (e.g., 2,000 vs. 500) than those whose left digits are congruent with the longer string length (e.g., 5,000 vs. 200).

In the number line context, both of these approaches suggest that adult participants will estimate single-digit numbers (e.g., 0.8) as smaller than double-digit numbers (e.g., 0.80) as previously found with children (Tian & Siegler, 2017). Specifically, Huber and colleagues' model includes using the number of digits in determining decimal magnitude for comparison and therefore predicts specifically that quantities with fewer digits should lead to a smaller estimate on the number line. However, Varma and Karl's (2013) hypothesis makes an additional prediction regarding whole number interference for single-digit decimals on the number line task. Specifically, if the corresponding single-digit whole number is activated by a single-digit decimal ($0.8 = > 8$), then there will be larger underestimation for single-digit decimals closer to 1 because there is a larger distance between the actual and activated value. For example, 0.8 activates 8 rather than 80, a difference of 72; whereas 0.2 activates 2 rather than 20, a difference of 18. Thus, a third goal of the study was to examine whether string length interference impacts decimal number line estimation or whether digit magnitude interference plays a role in decimal underestimation, or both.

Priming Effects in Rational Numbers

Manipulating the order that tasks are completed is a tool to investigate how context affects performance. These manipulations have gone by several names: task order (e.g., Szkudlarek & Brannon, 2021), prompting (e.g., Boyer & Levine, 2015), and priming (e.g., Abreu-Mendoza et al., 2020). Priming typically refers to brief presentations immediately preceding a trial, which facilitates processing on that trial, while negative priming hinders processing (Roell et al., 2017, 2019). Here, we use the term priming in a neutral sense to invoke the way in which a task can activate a notational system, and then influence future processing. Studies examining nonsymbolic and symbolic magnitude with comparison and match-to-sample-tasks have yielded evidence of fragile magnitude understanding based on numerical context (Boyer & Levine, 2015; Hurst & Cordes, 2018a, 2018b; Szkudlarek & Brannon, 2021). In nonsymbolic proportional reasoning, children tend to struggle with discretized stimuli where counting information contradicts the proportional response (e.g., selecting the pictorial representation of 4/8 as larger than 3/5) (Jeong et al., 2007). Completing the task in a noncontinuous format, which emphasizes counting, immediately before the discretized task leads to even worse performance on these contradictory comparisons (Abreu-Mendoza et al., 2020; Hurst & Cordes, 2018a).

Similar phenomena were observed in tasks with symbolic formats. For example, Ren and Gunderson (2019) demonstrated that children primed with whole number comparison (or a flanker control task) prior to decimal comparison performed substantially worse on trials with incongruent rather than congruent whole number components (e.g., worse performance on 0.9 vs. 0.23 than 0.2 vs. 0.93). These differences between congruent and incongruent trials were not present when participants were primed with decimals (or fractions) before the decimal trials. Moreover, in trial-wise decimal priming studies, seeing an incongruent comparison before a congruent one slows performance relative to consecutive congruent trials (Roell et al., 2017, 2019).

Thus, both nonsymbolic and symbolic proportional reasoning as measured by comparison tasks are affected by the context of prior tasks. However, to our knowledge, no study has examined whether priming can alter magnitude estimation of decimals in a number line task. Though magnitude comparison and number line estimation tasks both measure magnitude knowledge, results from these tasks sometimes differ (see for a review, Schneider et al., 2018). Identifying this kind of priming effect would suggest that fragile decimal magnitude estimation transcends the specific experimental task. Thus, the final aim of the study was to examine whether priming with whole number stimuli affects later decimal number line estimation.

The Current Study

The goals of the current study were fourfold. The first goal was to investigate whether adults' magnitude estimates for decimals followed a linear or logarithmic pattern with carefully controlled decimal and equivalent whole number stimuli (i.e., decimal × 100). We conducted this research with adults to examine mature number line estimation abilities rather than measure developing skills in this area. We predicted that adults' estimation patterns would follow a linear trend because adults typically have more linear than logarithmic response patterns for number line estimation (Siegler et al., 2009).

The second goal was to examine whether there are any systematic patterns of errors in number line estimation, among proportionally equivalent decimals and whole numbers. Specifically, we examined directional error rather than the typical metric for number line estimation tasks, PAE. Using directional error allowed us to examine whether decimal stimuli are over- or underestimated relative to their actual value, and their whole number equivalents. We predicted that decimals would be underestimated because of heuristic-type thinking that decimals are "small" numbers (Schiller, 2020; Schiller & Siegler, 2022).

Relatedly, the third goal was to determine whether digit length affects decimal estimation. Specifically, are single-digit decimals (e.g., 0.8) underestimated more relative to their double-digit equivalents (e.g., 0.80)? We predicted this would be the case based on preliminary work on number line estimation in children (Tian & Siegler, 2017) and other work documenting string length interference in adults in comparison tasks (Coulanges et al., 2021; Desmet et al., 2010; Durkin & Rittle-Johnson, 2015; Huber et al., 2014; Roell et al., 2017, 2019; Varma & Karl, 2013). Furthermore, we examined Varma and Karl's (2013) proposal that activation of the corresponding single-digit whole number contributes to underestimation of single-digit decimals relative to their magnitude. Specifically, we predicted that larger tenths decimal stimuli (e.g., 0.8) would show greater underestimation than smaller stimuli (e.g., 0.2) because of greater mismatch between the actual magnitude and the whole number referent in larger stimuli.

Finally, the fourth goal was to examine whether working with whole numbers immediately before decimals resulted in greater underestimation of decimals. Based on the hypothesis that whole number interference drives decimal underestimation, we expected that estimating whole numbers before decimals would exacerbate this phenomenon. Together, these analyses paint a comprehensive picture of adults' number line estimation of decimal magnitudes.

Method

Participants

Participants were 96 Rutgers University—Newark undergraduate students. Due to experimenter error, seven participants self-selected the order in which they completed the tasks and hence were excluded. Furthermore, we also excluded one participant who answered less than 70% of problems in the allotted time limit (3 s) in each of the two number line conditions (decimals and whole numbers). Our final sample size was 88 undergraduates ($M_{age} = 20.22$ years, $SD = 1.65$, 31 male and 57 female). For race/ethnic identity, 18% were Black/African American, 31% were Hispanic/Latino, 19% were Asian/Pacific Islander, 16% were Middle Eastern/Arab/Persian, and 6% were White/European. The remaining participants identified as other/multiracial (9%). The undergraduates were from various academic majors, including psychology (32%), biology/medical imaging (16%), neuroscience (12%), criminal justice (7%), business/accounting (5%), computer science (5%), arts and graphic design (2%), journalism and media studies (1%), public administration (1%), and mathematics (1%). The remaining participants were undecided (18%).

Using G*Power (Faul et al., 2009), we performed a sensitivity power analysis to determine the smallest detectable effect size with our current sample of 88 participants with 80% power and $\alpha = 0.05$. Such analysis indicated that the smallest detectable effect size corresponded with a $\eta_p^2 = 0.04$ (i.e., a small effect size). Notably, past studies of fraction number line estimation find that fractions with smaller components (e.g., 8/10) were estimated as smaller than the same magnitude presented with larger components (e.g., 20/25) (Braithwaite & Siegler, 2018a). The relevant effect size for this result was $\eta_p^2 = 0.31$, which was reported as generalized η^2 (η_g^2) = 0.13, further confirming that our sample size was sufficiently powered to detect comparable effects.

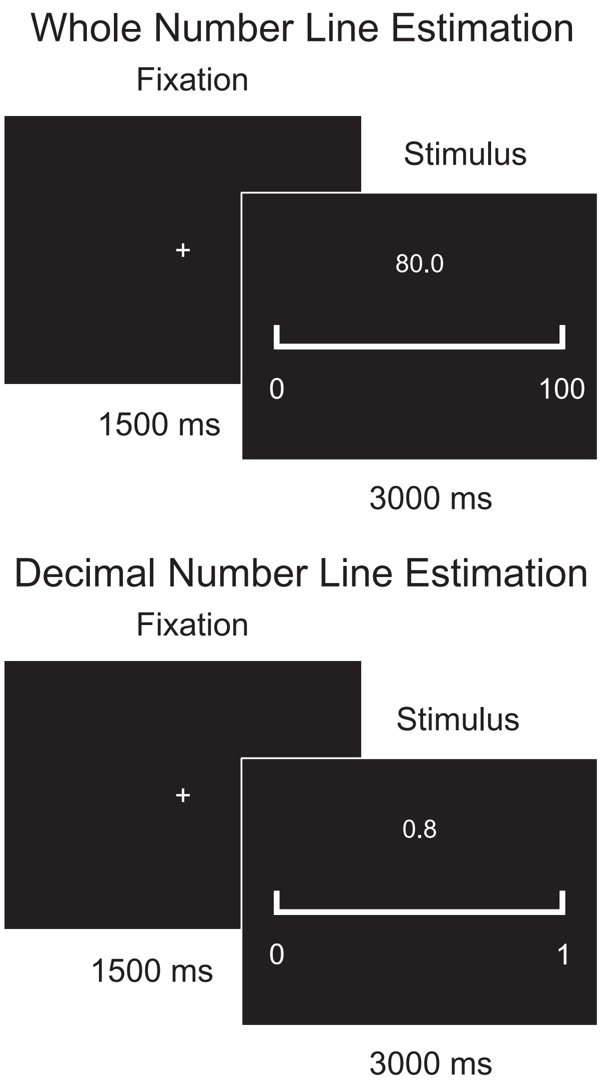
General Procedure

Data from the present study was collected as part of a larger project on college students' understanding of fractions and decimals (Rosenberg-Lee et al., 2022). Trained research assistants evaluated participants individually in-person. Participants were assessed on a set of math and executive function measures, which are not considered here. Specifically, participants completed paper-and-pencil assessments and computerized tasks in the following order: the Addition and Subtraction subtests of the Wechsler Individual Achievement Test-Third Edition (WIAT-III; Wechsler, 2009), the Spinners task (Jeong et al., 2007), the Hearts and Flower task (Davidson et al., 2006), a fraction comparison task, the Math Fluency and Calculation subtests of the Woodcock-Johnson III (Woodcock et al., 2001), a decimal comparison task, the Color-Word Stroop task (Stroop, 1992), the Backward Spatial Span task, this number line estimation task, and a demographic questionnaire on the survey platform, Qualtrics. Except for the pencil-and-paper standardized math assessments, all the other tasks were completed on laboratory laptop computers. The whole session took approximately ninety minutes. The number line estimation task, which is the focus of the present study, was the penultimate activity, preceding the demographic questionnaire. The number line task took less than 5 min.

Number Line Estimation

The number line estimation task was implemented in PsychoPy 1.85.2 (Peirce, 2007), on a 14-in. Lenovo ThinkPad laptop. Task order was counterbalanced by participant (e.g., half of the participants completed whole number trials first and the other half completed decimal trials first). The task began with a practice trial consisting of either 0.5 or 50.0, depending on the counterbalanced condition. Participants were given the instructions, "In this game, you will see numbers and a number line. Your task will be to decide where on the number line the number should be placed." Then, participants were given three seconds to place the number on the number line. To minimize visual dissimilarity between whole numbers and decimals, the whole numbers were presented with a decimal point and a zero in the tenths place (e.g., 80.0) and decimals were presented with a zero in the ones place (e.g., 0.80). For decimal trials, a 0–1 number line was presented and participants used the computer's mouse to select the position they thought best estimated the magnitude of the decimal. The only aspect that differed for whole number trials was that participants were presented a 0–100 number line (Figure 1). This range was chosen because it is an easy task where adult participants should be extremely accurate in their estimates (Siegler et al., 2009). Further, this range enabled us to measure their estimates for the proportionally equivalent decimal values on the 0–1 number line.

Figure 1
Schematic of the Number Line Task for Whole Numbers (Top) and Decimals (Bottom)



Note. Each number system was presented individually, with either the whole number or decimal block presented first. A fixation cross was presented for 1.5 s before each trial and then each trial lasted 3 s or until participants responded.

Regardless of the number type, all trials started with a fixation cross that remained on the screen for 1.5 s, followed by the number line and the whole number or decimal, which remained on screen for 3 s or until participants responded by clicking on the number line using the mouse (Figure 1).

The stimuli comprised decimals and equivalent whole numbers (Table 1). The decimal values consisted of double-digit decimals with either a 0 in the tenths place (Units, e.g., 0.08) or a 0 in the hundredths place (Decades, e.g., 0.80). Decimals without a zero in either the tenths or hundredths place were also included (Within-Decades, e.g., 0.82), one per decade. Finally, the task included single-digit decimals (Tenths, e.g., 0.8). Whole number stimuli were computed by multiplying the decimal value by 100 (e.g., 0.08 = >8). As Decades and Tenths are numerically equivalent, there is no Whole number expression of the Tenths stimuli. There were nine decimal and whole number trials presented for each category, for a total of 36 decimals and 27 whole numbers. In the analyses, we opted to remove trials consisting of 0.5, 0.50, and 50 from the data set, reasoning that participants are most familiar with decimals equivalent to half (Braithwaite & Siegler, 2018b; Fitzsimmons et al., 2020) and they were presented as practice trials. Thus, in the analyses, there were a total of 34 decimal trials and 26 whole number trials. The Appendix includes the full set of stimuli.

Statistical Analyses

Statistical analyses were conducted in R 3.5.3 (R Core Team, 2019) and a html version of a R-markdown file reporting all analyses is posted to Open Science Framework (https://osf.io/kvbf8/?view_only=ce32ad47c8d2455cb644f36b5d19d788). Directional error was calculated to determine whether quantities were over- or underestimated. Thus, if a participant was presented with 80, and placed it at 75 on a 0–100 number line, their directional error would be $75–80 = −5$. For purposes of analyses, the decimal and whole number magnitudes were put in the same scale (i.e., the whole number magnitudes were divided by 100). So, the aforementioned example would be −0.05, when proportionally scaled. To determine whether participants' number line placements were better fit by a logarithmic or linear pattern, we used linear mixed effect models. ANOVAs were used to determine whether condition, type, and/or their interaction had an effect on directional error of estimation. We also used mixed effect models to examine the effects of priming by stimulus presentation order.

Table 1
Examples From Each Category of Decimal and Whole Number Stimuli

	Condition	
Type	Decimal	Whole
Units	0.08	8.0
Within-Decades	0.82	82.0
Decades	0.80	80.0
Tenths	0.8	–

All mixed model analyses used the *lmer* function from the lme4 package in R (Bates et al., 2015). As part of this package, significance was established using Satterthwaite's method for estimating degrees of freedom. For posthoc analyses, we used functions from the emmeans package (emmeans and emtrends) in R (Lenth et al., 2018). This package allows posthoc analyses in models involving interactions between categorical factors and continuous predictors as well as simple slope analyses.

Results

Linear or Logarithmic Fit

Figure 2 presents the number line estimates for the Decimal and Whole numbers in the three, paired conditions (Units, Decades, and Within-Decades).

To test whether participants' number line placements were better fit by a logarithmic or linear function, we used linear mixed effect models. Model 1 included as predictors linear magnitude and condition (Whole vs. Decimal). Model 2 replaced linear magnitude with log-transformed magnitude. In both models, random effect terms were included for participant and item. The Decimal condition was used as the reference category for condition. Table 2 shows that both the linear and logarithmic magnitude terms are significant predictors of number line placement. However, when we included both linear and logarithmic magnitude terms in Model 3, only the linear term was significant (Table 2). In all the models, there were no interactions between the condition and function (linear, logarithmic), suggesting no differences in fit between Whole and Decimal numbers.

We also tested separately whether Decimal-Tenths were better fit by a linear or logarithmic pattern. As in the previous analysis, a random effect was included for participant and item. Table 3 shows that only the linear term is significant, when both the linear and logarithmic terms are included. Therefore, Decimal-Tenths are better fit by a linear pattern, like the other Decimal and Whole number types.

Directional Error

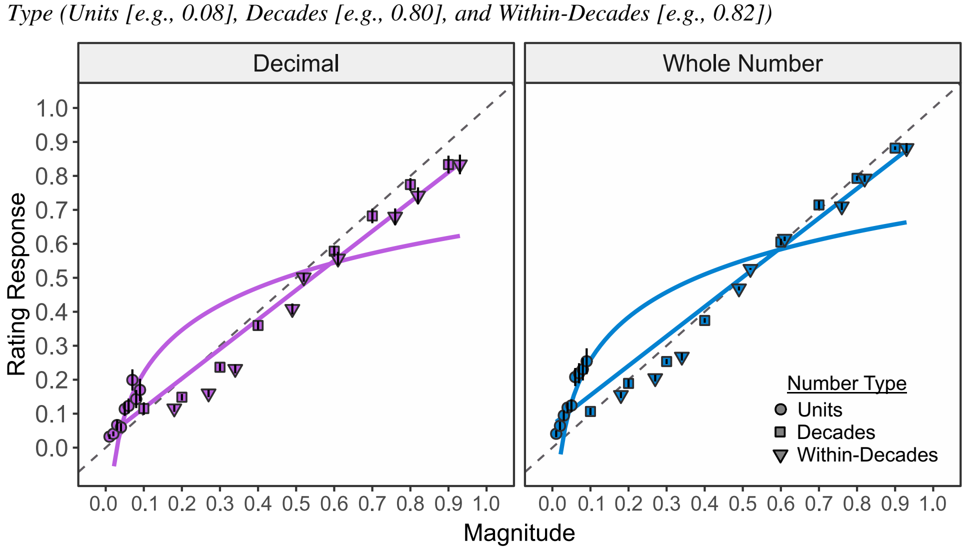
Typically, number line estimation analyses focus on PAE (e.g., Siegler et al., 2011; Siegler & Pyke, 2013). However, we opted to focus on directional error because PAE by design masks effects of direction, and inspection of the data suggested the direction of estimation error was not the same for all stimuli types. Specifically, for both Whole and Decimal numbers, participants overestimated for Units and underestimated for all other types (Table 4 and Figure 3).

To determine whether the condition (Decimal, Whole), type (Units, Decades, Within-Decades), and/or their interaction had an effect on directional error of estimation, we used a (2×3) repeated measures ANOVA. This analysis revealed a main effect of Condition (Decimal, Whole), $F(1, 87) = 17.41$, $p < .001$, $\eta_g^2 = 0.04$, and a main effect of Type (Units, Decades, Within-Decades), $F(2, 174) = 102.45$, $p < .01$, $\eta_g^2 = 0.26$, but no interaction between Condition and Type ($p = .40$). On average, Whole numbers are slightly overestimated ($M = 0.02$, $SD = 0.11$) and Decimals are slightly underestimated ($M = -0.02$, $SD = 0.12$) relative to their actual values. Further, Within-Decades ($M = -0.05$, $SD = 0.08$) and Decade stimuli are underestimated ($M = -0.02$, $SD = 0.07$), while Units are overestimated ($M = 0.08$, $SD = 0.13$). These analyses confirm that participants systematically underestimate decimals relative to their corresponding whole number equivalents.

To examine whether there was a difference in directional error on the stimuli with comparable proportional magnitudes (Decimal-Tenths, Decimal-Decades, and Whole-Decades), but different significant digits, we employed an ANOVA (1×3). Specifically, we wanted to determine whether expressing a decimal as a Tenth (e.g., 0.8) relative to a Decade (e.g., 0.80) exacerbated the

Figure 2

Logarithmic Versus Linear Fit of the Data by Condition (Decimals and Whole numbers) and Number Type (Units [e.g., 0.08], Decades [e.g., 0.80], and Within-Decades [e.g., 0.82])



Note. The data are better fit by the linear pattern for both decimals and whole numbers. See the online article for the color version of this figure.

Table 2
Linear Mixed Model Results for Number Line Placement of Units, Decades, and Within-Decades by Condition (Whole Vs. Decimal)

Fixed effects	Model 1 β (*SE*)	Model 2 β (*SE*)	Model 3 β (*SE*)
Intercept	.03 (.02)	.64 (.05)***	−.06 (.06)
Linear	.87 (.03)***	—	.99 (.08) ***
Logarithmic	—	.18 (.02)***	−.03 (.02)
Condition	.04 (.01)***	.04 (.01)***	.06 (.03)
Condition × Linear	.00 (.02)	—	−.02 (.04)
Condition × Log	—	.00 (.00)	.01 (.01)

*$p < .05$, **$p < .01$, ***$p < .001$.

directional error relative to its proportional whole number equivalent (e.g., 80). For this analysis, there was a main effect of Type, $F(2, 174) = 16.13$, $p < .001$, $\eta^2_g = 0.08$ (Figure 4). Posthoc *t*-tests confirmed that Decimal-Tenths (e.g., 0.8) were underestimated more than their comparable Decimal-Decade (e.g., 0.80), $t(87) = 3.8$, $p < .001$, and Whole-Decade (e.g., 80) trials, $t(87) = 4.8$, $p < .001$. Moreover, for Decade trials, Decimals are underestimated relative to Whole numbers, $t(87) = 2.4$, $p = .02$.

Together these results indicate that decimals are underestimated compared with their proportionally equivalent whole number magnitudes. Moreover, decimal string length exacerbates the underestimation, such that tenths decimals (e.g., 0.8) are perceived as smaller than their comparable decade decimals (e.g., 0.80).

Priming Effects

Next, we examined whether there was an effect of priming (i.e., completing the Whole number block before the Decimal block) and magnitude (i.e., larger decimals, like 0.8 versus smaller decimals like 0.2) on directional error for proportionally equivalent Decimal-Tenths, Decimal-Decades, and Whole-Decades (e.g., 0.8, 0.80, and 80). We used a linear mixed effect model, where magnitudes were standardized using *z*-scores to allow for comparison between decimals and their proportionally equivalent whole numbers on the same scale and to improve convergence of the models. In Model 1, we did not consider any effect of priming (whether whole numbers were presented first) but did include factors for Decimal-Decades and Decimal Tenths, with Whole-Decades as the reference level. In Model 2, presentation order (i.e., Whole-Priming) was coded dichotomously as 0 = Decimals and 1 = Whole numbers presented first. Presentation order and magnitude were included as fixed effects. As before, participant and item were included as random effects. Table 5 displays the results.

Table 3
Linear Mixed Model Results for Number Line Placement of Decimal-Tenths

Fixed effects	Model 1 β (*SE*)	Model 2 β (*SE*)	Model 3 β (*SE*)
Intercept	−.03 (.02)	.72 (.06)***	−.16 (.08)
Linear	.92 (.03)***	–	1.06 (.09)***
Logarithmic	–	.33 (.05)***	−.06 (.03)

*$p < .05$, **$p < .01$, ***$p < .001$.

Table 4
*Directional Error (*SD*) by Each Category of Decimal and Whole Number Stimuli*

Type	Condition: Decimal	Whole
Units	.06 (.10)	.10 (.15)
Within-Decades	−.08 (.11)	−.03 (.04)
Decades	−.04 (.10)	−.01 (.03)
Tenths	−.08 (.13)	–

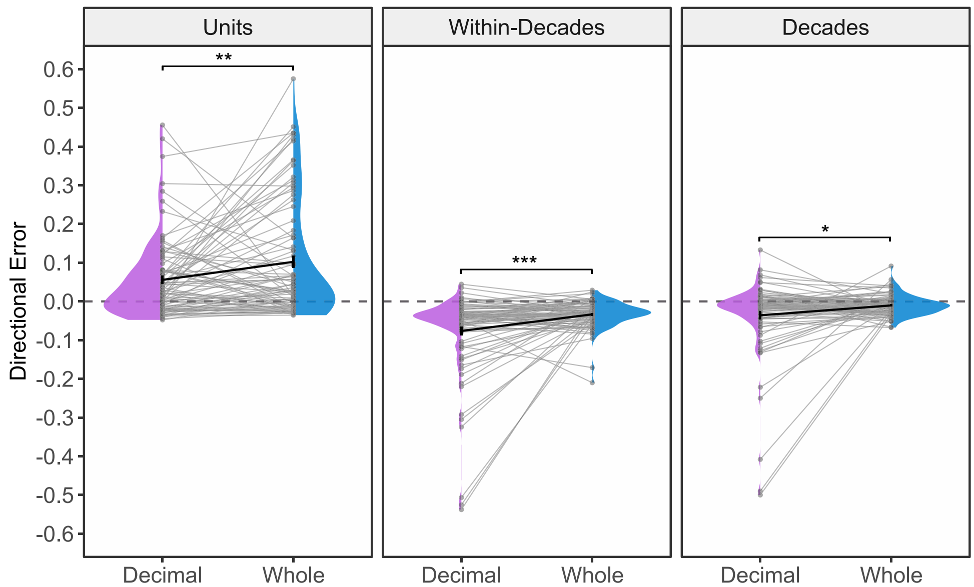
Note. All are different from 0 ($p < .001$).

In Model 1, the main effects of Decimal-Decades and Decimal-Tenths suggest that these decimals are underestimated relative to their proportionally equivalent whole numbers (Figure 5), confirming the results of the ANOVA analysis. While there was no main effect of Magnitude, the interaction between Type and Magnitude for Decimal-Tenths suggests that relative to the reference category (Whole-Decades), decimal magnitude affects estimates for Decimal-Tenths. Further, the fact that this interaction is negative indicates larger underestimation for larger decimals. To further confirm this effect for Decimal-Tenths but not the other categories, a simple slope analysis yielded evidence that Decimal-Tenths ($B = -0.02$, $p = .03$, 95% CI [−0.04, 0.00]), but not Decimal-Decades ($B = -0.01$, $p = .52$) or Whole-Decades ($B = 0.00$, $p = .74$), have a slope significantly different from 0. That is, larger tenths are underestimated more than smaller tenths, as would be predicted by the semantic interference proposal (Varma & Karl, 2013).

We added presentation order to Model 2 (Table 5 and Figure 6), finding interactions between type (Decimal-Tenths and Decimal-Decades) and presentation order (Decimal- or Whole-Priming). These results suggest that estimating whole numbers before decimals exacerbates decimal underestimation. Specifically, the Decimal-Tenths had greater underestimation during the Whole-Priming condition (*emmean* = −0.12) than the Decimal-Priming condition (*emmean* = −0.04; $B = 0.07$, $p < .001$, 95% CI [0.04, 0.10]). Similarly, Decimal-Decades were underestimated in the Whole-Priming condition (*emmean* = −0.06, *t*-ratio = −4.17, $p < .001$) but not in the Decimal-Priming condition (*emmean* = −0.01, *t*-ratio = −1.12, $p = .267$), a significant difference ($B = 0.04$, $p = .008$, [0.01, 0.08]. Moreover, the three-way interaction between Decimal-Tenths, Whole Number Priming, and Magnitude suggests that estimating whole numbers before decimals further exacerbates the underestimation for Decimal-Tenths, as it relates to magnitude ($B = 0.05$, $p < .001$, [0.03, 0.07]). That is, larger Decimal-Tenths (e.g., 0.8) are underestimated more than smaller Decimal-Tenths (e.g., 0.2). These findings suggest that, after working with whole numbers, magnitudes for single-digit numbers are activated more than double-digit equivalents (i.e., 8 rather than 80). Interestingly, the Decimal-Decades had a significantly steeper slope of performance across trials in the Whole-Priming condition than the Decimal priming condition (posthoc test: $B = 0.04$, $p < .001$, [0.02, 0.06]), suggesting some effect of magnitude on these stimuli. The slope of performance for whole number line estimation was not affected by whether they saw decimals or whole numbers first (posthoc test: $B = 0.02$, $p = .108$, [−0.004, 0.038]). Notably, there were no other interactions, including no interaction between magnitude, priming, and Decimal-Decades. That is, magnitude-based

Figure 3

Directional Error by Stimulus Type (Units, Within-Decades, Decades) by Condition (Decimal and Whole Number)



Note. Rain clouds reveal distributions for directional error, with the means highlighted in black. Lines connecting rain clouds display individual data by condition within the different number types. There is a main effect of condition, such that Decimals are underestimated relative to Whole numbers. There is also an effect of type, such that Units are overestimated and Within-Decades and Decades are underestimated. See the online article for the color version of this figure.
$^{*}p < .05$, $^{**}p < .01$, $^{***}p < .001$.

interference was exclusive to single-digit decimals, as predicted by the semantic interference account (Varma & Karl, 2013).

This analysis also allows us to assess the effects of the number of digits in the absence of Whole-Priming. Specifically, in the Decimal-Priming condition, Decimal-Tenths were significantly underestimated (*emmean* = −0.04, $p = .002$, 95% CI [−0.07, −0.02]) relative to their actual value, whereas, Decimal-Decades were not (*emmean* = −0.01, $p = .26$, [−0.04, 0.01]), and the difference between them was significant ($B = 0.03$, $p = .005$, [0.01, 0.05]). That is, single-digit decimals (0.8) are perceived as smaller than their equivalent double-digit version (0.80), even without whole number priming.

Discussion

The current work investigated adults' number line estimation for single- and double-digit decimals and their proportionally equivalent whole numbers (e.g., 0.8 and 0.80 on a 0–1 number line and 80 on 0–100 number line). Using carefully chosen stimuli, we found that adults have linear response patterns on the number line task for both decimals and whole numbers, but that decimals were systematically underestimated relative to comparable whole numbers. Moreover, decimal string length worsened the underestimation, such that single-digit decimals (e.g., 0.8) were perceived as smaller than their equivalent double-digit decimals (e.g., 0.80). Finally, presenting whole number stimuli before decimal stimuli further exacerbated decimal underestimation, relative to the magnitude of the stimuli.

Linear Not Logarithmic Decimal Number Line Estimation

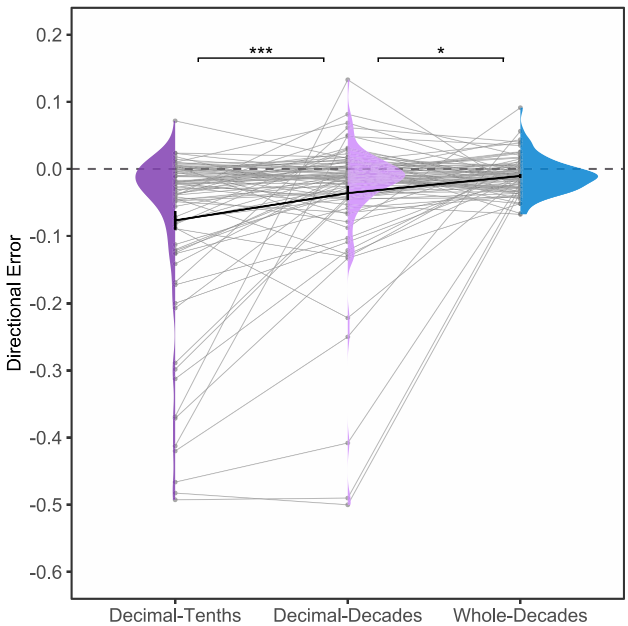
The results found here replicate earlier work reporting linear response patterns for decimal numbers when measured on a number line task. Prior reports of linear rather than logarithmic response patterns for decimals (Iuculano & Butterworth, 2011) did not explicitly account for string length. Thus, it was unclear whether the linear response pattern would hold for decimal magnitudes with differing digit length (e.g., 0.8 and 0.80), given string length effects found in decimal comparison studies (Huber et al., 2014; Varma & Karl, 2013).

Our finding that decimal magnitudes follow a linear response pattern with well-matched stimuli dovetails with research suggesting an integrated theory of numerical development (Siegler et al., 2011) and more recent research demonstrating parallels between fraction and decimal arithmetic (Braithwaite, McMullen, & Hurst 2022; Braithwaite, Sprague, & Siegler, 2022). Indeed, the current work suggests that decimal and whole number magnitudes are estimated similarly. However, there is unique and systematic bias within that linear response pattern, relating to all decimals, and especially single-digit decimals when primed with a whole number context.

Decimals Are Underestimated Relative to Whole Numbers

The results from our number line estimation task suggest that there is systematic underestimation of decimals. Concentrating first on all

Figure 4
Directional Error for Each Type of Proportionally Equivalent Number (Decimal-Tenths, Decimal-Decades, Whole-Decades)



Note. Decimals are underestimated compared with their proportionally equivalent whole numbers (e.g., 0.8 and 0.80 are underestimated relative to 80). Shorter decimal string length (i.e., single- vs. double-digit decimals) exacerbates the underestimation. See the online article for the color version of this figure.
*$p < .05$, **$p < .01$, ***$p < .001$.

the double-digit decimals (Units, Decades, Within-Decades), we found that they were always underestimated relative to whole numbers by about 4%. Interestingly, for both whole and decimals, the Unit (e.g., 8, 0.08) stimuli were slightly overestimated relative to their actual value. This effect might reflect the nonuniform stimuli selection, contributing to poor estimation at the lower end of the scale (and the strong logarithmic fits to that section of the data).

Table 5
Linear Mixed Model Results for Directional Error Without (Model 1) or With Priming (Model 2)

Fixed effects	Model 1 β (*SE*)	Model 2 β (*SE*)
Intercept	−.01 (.01)	−.01 (.01)
Decimal-Decades	−.02 (.01)**	−.01 (.01)
Decimal-Tenths	−.07 (.01)***	−.03 (.01)***
Magnitude	.00 (.00)	.01 (.02)
Decimal-Decades × Magnitude	−.01 (.01)	.00 (.01)
Decimal-Tenths × Magnitude	−.03 (.01)**	−.01 (.01)
Whole-Priming	—	−.00 (.01)
Decimal-Decades × Whole-Priming	—	−.04 (.02)**
Decimal-Tenths × Whole-Priming	—	−.07 (.02)***
Whole-Priming × Magnitude	—	−.02 (.01)
Decimal-Decades × Magnitude × Whole-Priming	—	−.02 (.02)
Decimal-Tenths × Magnitude × Whole-Priming	—	−.03 (.02)*

*$p < .05$, **$p < .01$, ***$p < .001$.

Indeed, the distribution of types of stimuli in a set can impact numerical processing, as has been observed in whole number comparison studies (Macizo & Herrera, 2010, 2013; Moeller et al., 2011, 2013). Nevertheless, decimals showed less overestimation and there was no interaction between number system and stimulus type.

General underestimation across number systems has been observed in prior work, which led to our initial interest in examining directional error rather than PAE. For example, underestimation has been observed in the estimation of the quantity of dots in arrays (Izard & Dehaene, 2008). Evidence from studies examining the bisection of physical lines (Longo & Lourenco, 2007) and generating random numbers (Loetscher & Brugger, 2007) suggested a left bias, leading to underestimation. However, we did not observe general underestimation for all stimuli, rather finding a specific effect of decimals underestimated relative to whole numbers.

Decimal underestimation relative to their proportionally equivalent whole numbers converges with recent cross-notation research in children (Schiller, 2020; Schiller & Siegler, 2022). Specifically, decimals were perceived as smaller than percentages in cross-notation comparisons. For example, cross-notation comparison accuracy was worse when the decimal was larger than the percentage (e.g., 25% vs. 0.40) than when the comparison involved a percentage being larger than the decimal (e.g., 40% vs. 0.25), despite identical numerical distance between the compared values. Conceivably, participants in that study may have been treating percentages as whole numbers in the cross-notation comparisons because they are often colloquially referred to as whole numbers (e.g., "She earned a 100 on her test."). Future work should examine the degree to which children and adults estimate percentages similarly to whole numbers and if decimals are underestimated on the number line more than their equivalent percentages.

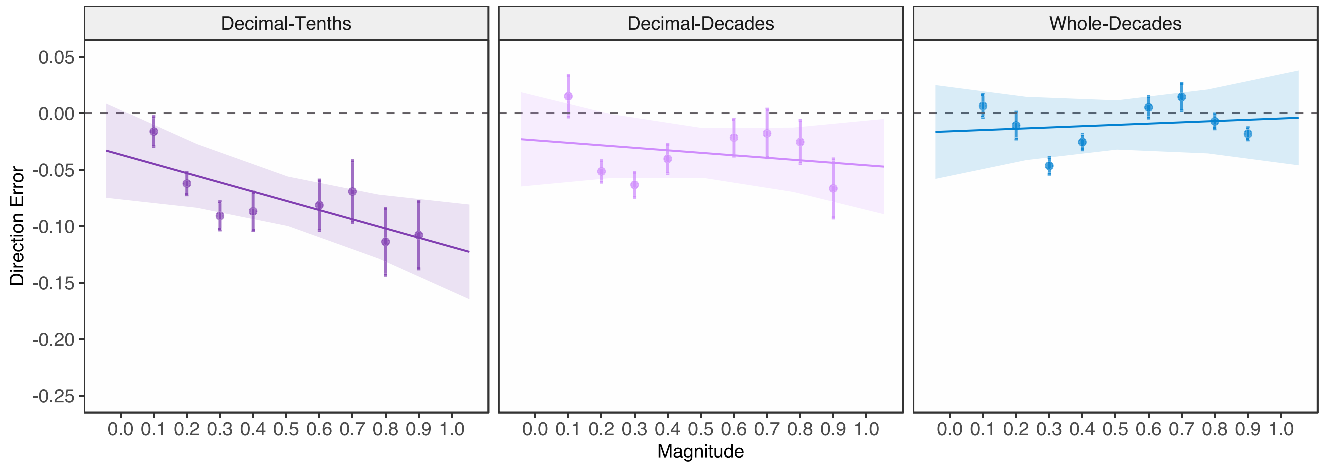
Decimal Number Line Estimation Is Impacted by String Length, Digit Magnitude, and Priming

A robust phenomenon in studies on decimal comparison is lower accuracy and slower response times on comparisons that are incongruent with whole number knowledge (e.g., 0.9 vs. 0.23 because $23 > 9$ but $0.23 < 0.9$) (Avgerinou & Tolmie, 2020; Coulanges et al., 2021; Huber et al., 2014; Ren & Gunderson, 2019; Varma & Karl, 2013). Two explanations have been posited for this effect. First, Huber and colleagues (2014) suggested this effect on decimal magnitude processing can be explained by string length effects, that is, our knowledge that longer strings indicate larger numbers. Second, Varma and Karl (2013) further suggested the magnitude of the presented digits may also interfere with decimal processing. That is, 0.8 activates the magnitude for 8 rather than 80, which induces more interference than for 0.2, which would activate 2 rather than 20. Unfortunately, stimuli employed thus far in magnitude comparison tasks do not allow for direct examination of both string-length and magnitude effects on estimation.

To our knowledge, this is the first study to provide direct evidence that decimal magnitude processing is impacted by *both* string length and digit magnitude. In accordance with Huber and colleagues' (2014) work with decimals, we found a main effect of string length, suggesting single-digit decimals are underestimated relative to double-digit decimals (Figure 5 and Table 4). Notably, given the effects of priming discussed below, we also found that underestimation of single-digit decimals relative to double-digit ones is present

Figure 5

Predicted and Observed Values for Directional Error by Type (Decimal-Tenths, Decimal-Decades, Whole-Decades) and Magnitudes



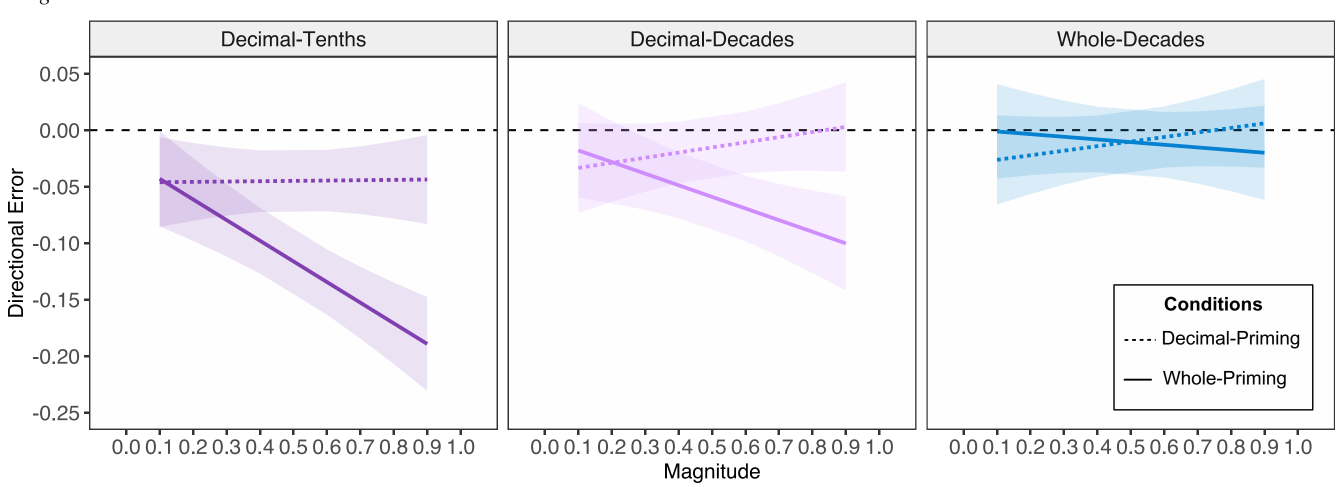
Note. Decimals are underestimated more than their proportionally equivalent whole numbers (e.g., 0.8 and 0.80 are underestimated relative to 80). Further, among Decimal-Tenths larger decimals (e.g., 0.8) are underestimated more than smaller (e.g., 0.2). Regression lines represent the estimates from the linear mixed models and shaded areas represent the 95% CI. Dots represent the observed means and vertical lines represent ± 1 *SE*. See the online article for the color version of this figure.

even among participants who estimated decimals before whole numbers. Huber and colleagues (2014) propose that the magnitude of each position is compared as well as the string length. Recent research suggests that both the string length and the left-digit magnitude simultaneously impact large whole number processing (García-Orza et al., 2023; Lozin & Pinhas, 2022). For example, Lozin and Pinhas (2022) found that the left digit also impacts adults' magnitude comparison speed for a wide range of numbers, from tens to trillions. These results suggest an update to Huber to say that left most digits are also compared even in different place values.

In line with Varma and Karl (2013), we also found evidence for magnitude effects, that is, larger underestimation for decimals closer to 1. Importantly, when we considered priming, it was clear that only the whole number priming participants showed the effect of greater underestimation for larger decimals (Decimal-Tenths). There was a trend toward magnitude effect for double-digit decimals (Decimal-Decades) but a stronger effect for single-digit decimals (Decimal-Tenths) when primed with whole numbers. This pattern of results suggests that the two posited explanations for this phenomenon (Huber et al., 2014; Varma & Karl, 2013) may stem from

Figure 6

Directional Error by Type (Decimal-Tenths, Decimal-Decades, Whole-Decades), Priming Condition (Decimal- Vs. Whole-Priming) and Magnitude



Note. Estimating whole numbers before decimals exacerbates decimal underestimation, especially for Decimal-Tenths. Regression lines represent the estimates from the linear mixed models and shaded areas represent the 95% confidence interval. (Observed values omitted for clarity.) See the online article for the color version of this figure.

difference sources. The physical size of the stimuli may always exert a force on participants' performance, while whole number priming may activate the semantic referent of the stimuli, thus inducing further magnitude-based interference. Future research should consider the effects on overall underestimation versus magnitude-based underestimation, if the string length were varied further (i.e., decimal stimuli with three digits or more).

More broadly, these priming results provide evidence that decimal magnitude processing is impacted by the context of activities that are presented immediately before decimal number line estimation. To our knowledge, this is the first study to provide evidence of priming effects for decimal magnitude estimation on a number line estimation task, building on previous observations of priming effects in magnitude comparison and match-to-sample tasks (Abreu-Mendoza et al., 2020; Boyer & Levine, 2015; Hurst & Cordes, 2018a; Szkudlarek & Brannon, 2021). One might think that comparison more naturally lends itself to interference effects than number line estimation. For example, comparing decimals, which are incongruent with whole number properties (e.g., 0.9 and 0.23 because $23 > 9$ but $0.23 < 0.9$), likely requires overcoming interference from whole number understanding that more digits result in bigger numbers. Indeed, priming with decimal comparison that was incongruent with whole number properties (i.e., 1.45 vs. 1.5) resulted in less efficient decimal and even line length comparison (Roell et al., 2017, 2019). Given the documented differences between number line estimation and magnitude comparison (for a review see Schneider et al., 2018), conceivably, placing one number at a time on a number line might not involve interference from whole numbers. However, we found evidence of a block-wise priming effect on a number line task, suggesting that fragile decimal magnitude understanding transcends the specific experimental task. Moreover, these results suggest there may be a longer-lasting priming effect than the trial-wise effects found in negative priming studies (Roell et al., 2017, 2019). In sum, our results suggest that estimating whole numbers on number lines activates whole number magnitudes for decimal numbers, leading to interference effects.

A limitation of the current work is that we do not have a non-numerical priming condition to act as a control for the priming effects. For example, Ren and Gunderson (2019) found that the non-numerical control priming condition (i.e., the flanker task) had similar effects to the whole number priming condition, namely, worse performance on a decimal comparison task relative to a fraction priming condition. This pattern of results suggests that among children, the default state is one where whole number knowledge interferes. By contrast, we found that undergraduate students had fairly accurate number line estimates when they were asked to place decimals on the number line before working with whole numbers. Of note, participants had completed fraction and decimal comparison tasks prior to this task, which might have acted like a rational number priming condition. Including a non-numerical control condition and starting with number line estimation in future studies will help discern the specific role of whole number priming in decimal underestimation. Relatedly, the current study also included other tasks (e.g., standardized math measures, executive function tasks) prior to the number line estimation task, which is the focus of this study. Explicitly manipulating the task sequence would be needed to determine if these other tasks influenced the results reported here. Another focus for future research is to take into account task timing as the current study had a time limit, while previous number line studies in children were untimed. Another feature of our design, which differs from previous work, is presenting whole numbers in "decimal format" (e.g., 80.0). Whether typical whole number format (e.g., 80) and omitting leading zeros on the decimals (e.g., 0.8) would further exacerbate these effects remains to be studied.

Theoretical Implications of the Current Work

We focused on decimal number line estimation for adults, who should have mature estimation skills for decimals. A recent conference proceeding also showed that 6th and 7th grade students' decimal number line estimation was influenced by the number of digits, where single-digit decimals were underestimated more than double-digit decimals (Tian & Siegler, 2017). Here, we observed an analogous phenomenon with adults. An interesting open question is whether these underestimation effects are stable across development, or narrow with further experience. Potentially, children may always show whole number magnitude interference, whereas adults only display it when prompted to engage with whole numbers first. A similar phenomenon has been found in whole number estimation where adults who have linear response patterns can produce logarithmic response patterns with presentation of less familiar numerical stimuli or number line anchors (Chesney & Matthews, 2013; Hurst et al., 2014; Landy et al., 2013, 2017).

The current study also has implications for experimental research methods. Researchers should carefully consider the string length of decimal stimuli (i.e., single- vs. double- or triple-digit decimals). For example, Iuculano and Butterworth (2011) utilized equivalent fraction and decimal stimuli but it was unclear how decimal string length was controlled for. Here, single-digit decimals (e.g., 0.8) were underestimated relative to their equivalent double-digit decimals (e.g., 0.80). While interference effects have been observed in decimal comparisons with differing digit lengths (Coulanges et al., 2021; Desmet et al., 2010; Durkin & Rittle-Johnson, 2015; Huber et al., 2014; Roell et al., 2017, 2019; Varma & Karl, 2013), these effects had not yet been observed on number line tasks with adults. Thus, decimal string length should be carefully considered regardless of the task format. For example, Mock et al. (2018) investigated decimal representation in the brain, finding that they were more similar to pie charts and dot proportions than fractions. However, they only used double-digit decimals, thus not capturing the feature of decimals—decoupling magnitude from symbolic presentation—that make it conceptually more similar to fractions (Rosenberg-Lee, 2021). Another concern raised by these results is the effect of task order. For example, Kallai and Tzelgov's (2014) suggestion that magnitude of decimals with place values less than one (i.e., tenths, hundredths) are not processed automatically may have been subject to unintended priming effects. Specifically, the experiments that yielded evidence of a focus on string length rather than place value magnitude were preceded by a task where the participants had to identify the physically larger string length. Thus, researchers should also carefully consider the presentation order of numerical notations and counterbalance notation presentation order whenever possible.

Notably, we detected considerable individual variability in decimal performance with some participants showing no error and others erring by as much as 50% (see Figures 3 and 4). Future work aimed at examining individual differences in number line estimation could illuminate the practical importance of this phenomenon. For instance, do individuals who are more susceptible to underestimating 0.8 than 0.80 on the number line perform worse on other math measures relative to those who have less malleable decimal response patterns? Do individuals who have greater cross-notation knowledge (i.e., greater facility translating amongst fractions, decimals, and percentages) also have less fragile estimates of decimal magnitude? Establishing that susceptibility to whole number interference represents a stable individual trait, with consequences across rational number domains, would make it a fruitful target for educational intervention.

Educational Implications of the Current Work

There have been numerous proposals that rational number difficulties can be ameliorated by teaching decimals prior to fractions and percentages (see for a review, Tian & Siegler, 2018). Specifically, decimals are thought to be free from issues stemming from the bipartite structure of fractions (i.e., a/b). Further, their place value structure is similar to whole numbers making them a nice segue into the realm of rational numbers. However, our results shed light on a broad category of difficulties with rational numbers, the decoupling of magnitude from notation. In fact, fractions are also influenced by smaller versus larger component surface-level features, with students indicating that 20/25 is larger than 4/5 (Braithwaite & Siegler, 2018a). Potentially, informing educators about these features of decimals could help bridge connections between formats: for example, highlighting how decimals differ from whole numbers in that there are multiple ways of representing the same value could provide a foundation for learning about this feature of fractions.

These findings also shed light on the commonalities among notations. Decimals, like fractions and other rational numbers, can be expressed in multiple representations. Moreover, each whole number can be represented in many ways as fractions, decimals, and percentages (e.g., $2 = 8/4 = 2.0, = 200\%$, etc.). While technically there are also many representations of whole numbers (e.g., $2 = 02 = 002$) within the whole number notation, these representations are far less common in everyday life than the varied representations of decimal magnitudes (e.g., $0.2 = 0.20 = 0.200$). Moreover, the English language has names for these decimal variations (e.g., "two-tenths," "two-hundredths," "two-hundred thousandths," etc.), while whole numbers with appended zeros are not named differently (that is, the whole number 2 is named "two", no matter how many zeros it has appended to its left side). Although one might say it as "zero-two" or "zero-zero-two" or "two point zero," etc., these names are transparent to their written expression. Lesion studies demonstrate that the ability to name multidigit numbers is separate from other math skills such as calculation (L. Cohen & Dehaene, 1991; Dotan & Friedmann, 2018; McCloskey, 1992). The multiple names for digits in the same position in decimal numbers, depending on the string length, might compound these number naming difficulties. Perhaps, understanding the relations among fractions and decimals as instantiations of the same magnitude expressed differently could promote better magnitude understanding and arithmetic performance (Braithwaite et al., 2022; Moss & Case, 1999; Schiller, 2020; Schiller & Siegler, 2022; Schiller, Siegler & Thompson, 2022). For example, a recent training study found that placing equivalent fraction, decimal, and percent values on number lines and emphasizing their position as being in the same location resulted in better outcomes for adults than practice placing fractions alone on number lines (Schiller et al., 2022). In general, integrated understanding of rational and whole numbers is crucial for successful numerical development (Siegler et al., 2011).

Conclusion

The current work converges with other lines of research that call into question the assumption that decimals are a straightforward extension of whole numbers. We found that adults systematically underestimate decimals relative to their proportionally equivalent whole numbers. Further, decimals with single- versus double-digits were perceived as smaller and that whole number priming lead to magnitude-based underestimation. Ultimately, despite their visual similarity to whole numbers, decimals, like other rational numbers, are not immune to interference from notational features and context.

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(*Appendices follow*)

Appendix

Number Line Estimation Stimuli

Table

Units	Decades		Within-Decades		Tenths	
Decimal	Whole	Decimal	Whole	Decimal	Whole	Decimal
0.01	1	0.10	10	0.18	18	0.1
0.02	2	0.20	20	0.27	27	0.2
0.03	3	0.30	30	0.34	34	0.3
0.04	4	0.40	40	0.49	49	0.4
0.05	5	0.50	50	0.52	52	0.5
0.06	6	0.60	60	0.61	61	0.6
0.07	7	0.70	70	0.76	76	0.7
0.08	8	0.80	80	0.82	82	0.8
0.09	9	0.90	90	0.93	93	0.9

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