Same, but Different: Sequential and Simultaneous Fraction Comparison Tasks Elicit Different Distance and Congruency Effects

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Abstract

How humans process fractions is a topic of debate in numerical cognition research. While some studies suggest that humans process the holistic magnitude of fractions, others suggest we process only the fraction components (numerators and denominators). Two cognitive effects present in fraction processing data have shaped this debate: the distance effect (better performance with fractions separated by a far numerical distance) and the congruency effect (better performance when individual numbers are larger in the larger fraction). In a study with 160 young adults, we compared distance and congruency effects across two task formats of fraction comparisons, using simultaneous and sequential presentation of stimuli. Results revealed that the distance effect and the congruency effect were stronger in the simultaneous task than in the sequential task. These findings suggest that participants used both holistic and componential strategies when comparing fractions and highlight that task formats should not be used interchangeably.

Keywords: fraction processing; fraction distance effect; fraction congruency effect; two-alternative forced choice task.

Introduction

Fraction knowledge is critical for advanced mathematics. In particular, conceptual understanding of fractions and proficiency with fraction operations are robust predictors of algebraic reasoning (Booth & Newton, 2012). Despite their importance, fractions are regarded as the most difficult topic in the elementary school mathematics curriculum. Even highly educated adults struggle with basic concepts, like indicating how many fractions lie between ½ and ¼ (infinite). Given the critical role of fractions in mathematical development and their inherent difficulty, understanding how humans process fraction magnitudes has become a central question in numerical cognition research.

There is ongoing debate about how humans process fraction magnitudes. According to the mental number line hypothesis, humans generally process numbers on a mental number line oriented from left (smaller magnitudes) to right (greater magnitudes; (Dehaene, 2003). This hypothesis posits that, as people acquire mathematical knowledge through schooling and enculturation, neuronal populations evolved to process non-symbolic numerical magnitudes become increasingly specialized in processing specific symbolic numbers. Using population coding , neuronal populations respond most strongly to a preferred magnitude while exhibiting weaker responses to other magnitudes (Nieder, 2016). For instance, neurons specialized for “2” peak for 2 but also activate for proximal magnitudes, like 1 or 3. In contrast, the neurons specialized for “2” show minimal activation in response to magnitudes such as 10, 11, or 12. With this representational schema, numbers further apart on the mental number line have more distinct neuronal tuning curves, while numbers closer together have more overlapping neuronal tuning curves across populations of neurons.

At the behavioral level, this distinct pattern of overlapping neural response to numerical magnitudes manifests as the ***distance effect*** (Hubbard et al., 2005). The distance effect occurs when people are faster and more accurate in judging numbers separated by a far distance (e.g., 1 vs. 9, distance = 8) than by a near distance (e.g., 1 vs. 2, distance = 1) (Moyer & Landauer, 1967). This effect may reflect a higher overlap in neural responses to numerical magnitudes separated by a near distance—which makes the comparison harder—and a lower overlap to numerical magnitudes separated by a far distance—which makes the comparison easier.

The distance effect in single-digit, whole number comparison tasks has been observed both in people with low and high levels of mathematics knowledge, across cultures, and throughout the lifespan (Ashkenazi et al., 2009; Hohol et al., 2020; Holloway & Ansari, 2009; Kadosh, 2008). The robustness of the distance effect suggests it is a hallmark of how single-digit whole numbers are processed in the human brain: along a unique mental number line. To date, it is less clear if humans also represent fraction magnitudes on a mental number line.

To evaluate whether fractions are processed along a mental number line, researchers have examined whether a distance effect, similar to that observed with whole numbers, emerges when comparing fractions. Some findings indicate that humans exhibit a distance effect modulated by the holistic

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distance between two fractions when comparing their magnitudes (Toomarian & Hubbard, 2018). For instance, Toomarian and Hubbard (2018) found that adult participants were more accurate and faster when comparing 1/9 to 7/8 (holistic distance = 0.76) than when comparing 1/9 to 2/8 (holistic distance = 0.14). These findings suggest that humans process holistic fraction magnitudes on a mental number line, similarly to single-digit whole numbers.

However, contrary evidence suggests that adults do not process fractions as a holistic magnitude with a place on the mental number line. Instead, they may rely on the individual magnitudes of numerators and denominators in fraction comparisons, treating fractions as whole numbers (Bonato et al., 2007; Obersteiner et al., 2013). For instance, when solving a comparison like 1/2 vs. 3/4, some people might focus only on the numerators, actually solving a single-digit whole number comparison (i.e., comparing 1 vs. 3). The findings call into question whether the mental number line extends to numerical magnitudes represented as fractions.

As analyses of distance effects have produced mixed results regarding holistic and componential processing of fractions, people have also investigated fraction processing by including experimental manipulations that contrast whole number processing with processing the fraction as a holistic representation (i.e., as a ratio) (Gómez et al., 2015; Obersteiner et al., 2013). This manipulation contrasts fractions comparisons where individual components signal which fraction is greater (i.e., congruent with ratio magnitude) with fraction pairs where the individual components are misleading (i.e., incongruent with ratio magnitude). For example, congruent trials include pairs where the greater fraction also has greater numerator, such as 1/4 vs. 5/6 (i.e., 1/4 < 5/6, and 1< 5). In contrast, incongruent trials include pairs where the fraction with a greater numerator has a smaller holistic magnitude, like 3/4 vs. 5/9 (i.e., 3/4 > 5/9, but 3<5). Participants using a componential strategy may show slower and less accurate responses in incongruent trials compared to congruent trials, which is known as the ***congruency effect*** (Morales et al., 2020; Van Hoof et al., 2013). This effect indicates a cognitive conflict arising from a reliance on componential strategies or a mixed use of componential and holistic strategies.

To empirically investigate these competing accounts, researchers have frequently relied on two-alternative forced choice tasks, which offer a controlled way to examine how people compare fractions (e.g., DeWolf & Vosniadou, 2015; Gómez et al., 2015; Obersteiner et al., 2013). In these tasks, participants are presented with two fraction magnitudes and asked to indicate which one is greater. Across studies, two main versions of fraction comparison tasks have been used: *sequential* and *simultaneous*. The *sequential* version of the task presents the fractions one at a time (e.g., “1/2” shown on a screen, followed by “7/8” shown on a subsequent screen). In contrast, the *simultaneous* version presents both fractions together on the same screen (e.g., “1/2” and “7/8” displayed side by side).

Sequential and simultaneous fraction comparison tasks have been used interchangeably (DeWolf et al., 2016; Ischebeck et al., 2010). However, it is unclear whether task format influences fraction distance and congruency effects. Whole number studies have found that the presentation format in two-alternative forced choice tasks influences how these numbers are processed (Zhang & Wang, 2005). Ganor-Stern and colleagues (2009) investigated whether people processed two-digit numbers in a holistic or componential way (i.e., processing units and decades separately) in simultaneous and sequential comparison tasks. They found that, in the simultaneous task, participants were faster to judge pairs when both the unit and decade digits indicated the larger magnitude (congruent trials, such as 23 vs. 59; 2 < 5, 3 < 9) than when they conflicted (incongruent trials, such as 29 vs. 53; 2 < 5, but 9 > 3). However, in the sequential task, no difference was observed between congruent and incongruent pairs. These results suggest componential processing in simultaneous tasks, and holistic processing in sequential tasks. These findings with whole number two-alternative forced choice tasks raise an important question: how does the presentation format of two-alternative forced choice fraction comparison tasks influence the distance and congruency effects? In the current study, we address this question. Given the bipartite nature of fractions and the cognitive demands of comparing holistic magnitudes or individual components, task format may significantly influence strategy use and, consequently, distance and congruency effects.

Here, we examined differences in the distance effect and the congruency effect across sequential and simultaneous versions of two-alternative forced choice fraction comparison tasks. We analyzed how participants’ performance differed across (1) various distances (from near to far), (2) congruent and incongruent trials, and (3) sequential and simultaneous fraction comparison tasks. We also investigated possible interactions between distance, congruency, and task format. If the distance and congruency effects are influenced by task format, we might observe significant interactions. In particular, if sequential tasks elicit holistic strategies and simultaneous tasks elicit componential strategies, as previously observed with whole numbers, then the distance effect may be more robust in the sequential task, whereas the congruency effect may be stronger in the simultaneous task.

Methods

Participants

Participants were psychology students recruited through the University’s online research participant pool platform and through flyers distributed throughout the psychology building. They were neurologically healthy, native English speakers, aged 18 to 35, with normal or corrected-to-normal vision and no color blindness. We pre-registered the study (https://osf.io/yzgws/?view_only=c70ca02cdc0f4600b2ee4d5a602701f9), aiming for a sample of 150 participants. However, we anticipated excluding some participants due to low data quality, as noted in our preregistration. Thus, we recruited a total of 166 students, who participated in the study and were compensated with research credits. Five participants did not complete all trials in the sequential task, with trial counts ranging from 1 to 34 (1, 17, 24, 31, and 34 trials completed, respectively). These participants were excluded for poor data quality. We excluded one additional participant due to an accuracy rate below 50% on the sequential task, which is consistent with random guessing in a two-alternative forced choice paradigm. Therefore, the final sample consisted of 160 participants (mean age = 19.18, sd = 1.24; 71% female; 90% Non-Hispanic; 56% White, 28% Asian, 13% Black, 2% other, 2% did not report their race).

General Procedures and Materials

This study was part of a larger project that adopted a within-subjects design. The study was deemed exempt by the University's Institutional Review Board. Participants completed two versions of a two-alternative forced choice fraction comparison task: one with sequential and one with simultaneous stimulus presentation (Figure 1). The testing session was conducted in our lab by trained research assistants following standardized scripts. First, participants provided an oral consent to participate and received instructions. Then, they completed the tasks, with short breaks offered between them, followed by a sociodemographic questionnaire.

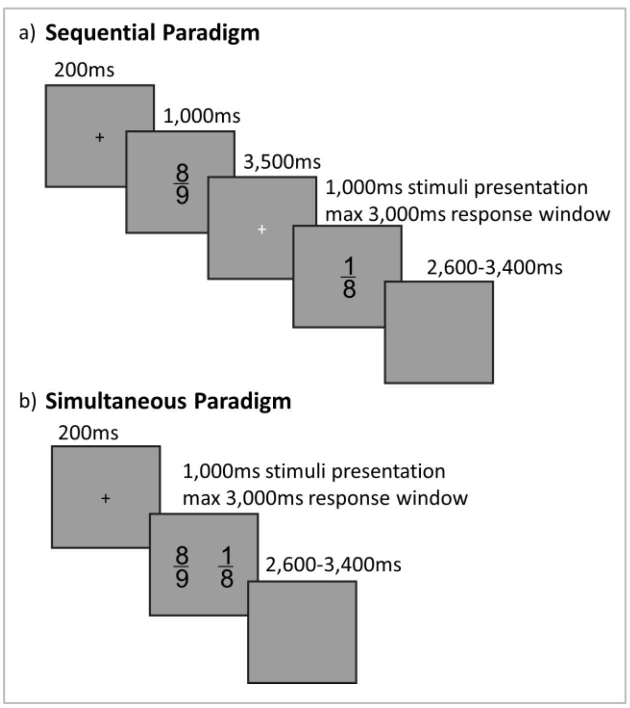

Figure 1: Sequential (a) and simultaneous (b) fraction comparison tasks.

In the sequential and simultaneous fraction comparison tasks (Figure 1), participants were presented with two fractions and instructed to identify the one with a greater magnitude. We adapted 40 fraction pairs from fraction comparison lists developed by Binzak and Hubbard (Binzak & Hubbard, 2020) and Dewolf and colleagues (DeWolf et al., 2016). These pairs consisted of proper, irreducible fractions composed of single-digit numerators and denominators. The fractions were separated by either a near or a far holistic distance, which ranged from 0.10 to 0.76. Each pair was either congruent or incongruent. In congruent pairs, (1) the greater fraction also had a greater numerator and denominator (e.g., 7/8 vs. 3/4, 7 > 3 and 8 > 4), or (2) both fractions shared the same denominator, and the greater fraction had a greater numerator (e.g., 8/9 vs. 4/9, 8 > 4). Incongruent trials were those in which this pattern did not apply, such that (1) the greater fraction had a smaller numerator and denominator (e.g., 3/8 vs. 1/2, 3 > 1 and 8 > 2), or (2) the greater fraction had a smaller denominator (e.g., 2/9 vs. 2/3, 9>3; 1/8 vs. 6/7, 8 > 7). Of the 40 pairs, 20 pairs were congruent, and 20 pairs were incongruent. Each pair was shown twice, resulting in a total of 80 trials, counterbalanced for which side the greater magnitude was displayed on. Participants were presented with these trials in a random order.

The experiments were programmed in PsychoPy and presented in a counterbalanced order on a 27-inch Apple iMac. Accordingly, half of the participants completed the simultaneous task first, while the other half began with the sequential task. The fractions were displayed in black Arial font (height = 0.3 normalized units, RGB = 0, 0, 0) against a gray background (RGB = 157, 157, 157). Participants indicated their responses using a standard U.S. QWERTY keyboard.

In the sequential task, comparison pairs were presented at the center (X = 0, Y = 0) of consecutive screens. Each task began with three practice trials that included feedback, followed by testing trials without feedback. At the start of each trial, participants saw a fixation cross for 200ms. Then, the first magnitude was presented for 1,000ms, followed by a 3,500ms inter-stimulus interval, and the second magnitude also shown for 1,000ms. Participants were instructed to respond as soon as they saw the second magnitude by pressing 'z' with their left index finger if the first stimulus was greater, or 'm' with their right index finger if the second stimulus was greater. Participants had up to 3,000ms to respond. Trials were separated by a mean intertrial interval of 3,000ms (range 2,600ms—3,400ms).

In the simultaneous task, comparison pairs were shown on the left side (X = -0.35, Y = 0) and right side of the screen (X = 0.35, Y = 0). Each task began with three practice trials that included feedback, followed by testing trials without feedback. At the start of each trial, participants saw a fixation cross for 200ms. Then, they were presented with two fractions on the screen for 1,000ms. They were instructed to press 'z' with their left index finger if the stimulus on the left side of the screen represented a greater magnitude. Conversely, if the stimulus on the right side of the screen was greater, they were instructed to press 'm' with their right index finger. Participants had up to 3,000ms to respond.

Trials were separated by a mean intertrial interval of 3,000ms (range 2,600ms—3,400ms).

We calculated the mean response time (RT) for each participant and excluded any trial where the RTs were slower or faster than three standard deviations from the individual means (2% of total trials excluded due to extreme RT). Additionally, we excluded trials with RTs faster than 200ms. The accuracy rate was our dependent variable of interest.

Results

Participants' performance in the sequential and simultaneous tasks

Table 1 presents participants' mean accuracy rates in the sequential and simultaneous fraction comparison tasks, broken down by distance and congruency conditions. Overall, participants showed high mean accuracy across both tasks and all conditions.

Table 1: Descriptive statistics

Accuracy	**Sequential**		**Simultaneous**	
	Mean	***sd***	***Mean***	***sd***
Overall	0.93	0.08	0.94	0.08
Distance				
Far	0.97	0.05	0.98	0.04
Near	0.90	0.10	0.90	0.09
Congruency				
Congruent	0.94	0.08	0.96	0.06
Incongruent	0.93	0.09	0.92	0.09

Effects of distance, congruency, and task format on participants' performance

To understand how experimental manipulations influenced participants' performance, we conducted a linear mixed model. The outcome variable was participants' mean accuracy. Distance (entered as a continuous measure), congruency (dummy coded: incongruent = 1, congruent = 0), and task format (dummy coded: simultaneous = 1, sequential = 0) were specified as fixed effects. We also analyzed interactions between these factors. To account for inter-individual variability, we included a random intercept for each participant. We also included a random slope for the interaction between holistic distance and congruency, allowing this effect to vary across participants. We anticipated that task format would interact with distance and congruency if sequential and simultaneous stimuli presentation influenced the strength of the distance and congruency effects. Conversely, if the distance and congruency effects were not influenced by task format, no interaction would be observed.

We conducted this analysis in R (version 4.3.0) and R studio (version 2023.03.1) using the glmer function from the lme4 package (Bates, 2018), and estimated p-values using the lmerTest package (Kuznetsova et al., 2022). We implemented the linear mixed models with a binomial error distribution and a logistic link function, using the "bobyqa" (Bound Optimization BY Quadratic Approximation) optimizer, with a maximum of 100,000 function evaluations. We explored interactions using simple slope analyses.

Table 2 summarizes the linear mixed model results. For each unit increase in distance, the odds of a correct response more than doubled, consistent with a distance effect. Incongruent trials had slightly lower odds of a correct response than congruent trials, but this main effect was not significant. Results also suggested that the odds of a correct response were higher in the simultaneous format. There were significant interactions between distance and congruency, as well as between distance and task format. There was also a significant interaction between congruency and task format. However, the three-way interaction between distance, congruency, and task format was not significant.

Table 2: Linear Mixed Model: How distance, congruency, and task format predict accuracy in fraction comparisons

Predictor	***OR***	***C.I.***	***p***
Distance	2.22	1.84, 2.68	<.001
Congruency (inc.)	0.88	0.68, 1.14	.338
Task (sim.)	1.93	1.54, 2.42	<.001
Distance x congruency (inc.)	1.45	1.11, 1.89	.006
Distance x task (sim.)	1.33	1.04, 1.70	.021
Congruency (inc.) x task (sim.)	0.58	0.43, 0.78	<.001
Distance x congruency (inc.) x task (sim.)	1.05	0.77, 1.45	.744

Note. AIC = 10,346.50. Inc = incongruent; Sim = simultaneous; OR = odds ratio; C.I. = 95% confidence interval.

We examined the significant interactions using *post-hoc* simple slope analyses. To illustrate the effects, Figure 2 presents mean accuracy across distance and congruency levels in the sequential and simultaneous tasks.

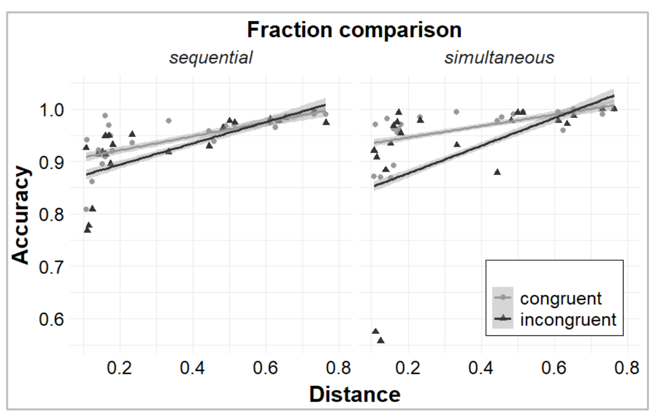

Figure 2: Accuracy in the fraction comparison tasks by distance, congruency, and task version.

Interaction between distance and congruency We tested this interaction by investigating how congruency predicted accuracy across different distance levels. When distance was very near (< 0.14), the odds of a correct response were lower in incongruent than congruent trials (*OR* = 0.38, $p < .001$), suggesting a congruency effect. A congruency effect was also observed at medium distances (i.e., between 0.14 and 0.58; *OR* = 0.59, $p < .001$). However, when fractions were numerically far apart (> 0.58), the congruency effect was not significant (*OR* = 1.02, $p = .909$). This result suggests that resolving conflicting information about fraction magnitudes may be easier in trials where the distance is far, making the task less demanding than in near-distance trials.

Interaction between distance and task format We tested this interaction by investigating how distance predicted accuracy in the simultaneous task and the sequential task. In both task formats, the odds of a correct response increased with greater numerical distance, indicating a distance effect. However, the distance effect was stronger in the simultaneous task (OR = 3.15 $p < .001$) than the sequential task (*OR* = 2.25, $p < .001$). This finding suggests that the cost of comparing fractions separated by near distances, relative to far distances, is lower in the sequential task than in the simultaneous task.

Interaction between congruency and task format We tested this interaction by investigating how congruency predicted accuracy in the simultaneous task and the sequential task. In both task formats, the odds of a correct response were higher in congruent than incongruent trials, suggesting a congruency effect. However, the congruency effect was stronger in the simultaneous task (*OR* = 0.44, $p < .001$) than the sequential task (OR = 0.77, $p < .001$). This finding suggests that the cost of comparing incongruent versus congruent trials is greater in the simultaneous task than in the sequential task.

Discussion

This study examined how two key effects in fraction processing—the distance effect and the congruency effect (Gómez et al., 2015; Obersteiner et al., 2013; Toomarian & Hubbard, 2018)—differ across sequential and simultaneous comparison tasks. Prior work has shown that simultaneous tasks encourage componential processing in two-digit whole number comparisons, whereas sequential tasks encourage holistic processing (Ganor-Stern et al., 2009). Based on this, we predicted a similar pattern for fractions: a stronger distance effect in the sequential task (indicating holistic processing) and a stronger congruency effect in the simultaneous task (indicating componential processing). However, our findings revealed that the distance and congruency effects were stronger in the simultaneous task. Additionally, we observed that the congruency effect was stronger when distances were near, and weaker when distances were far. These findings suggest that participants adopted a mix of holistic and componential strategies, and that comparing near distances relative to far distances, and incongruent relative to congruent trials was harder (i.e., marked by lower accuracy) in the simultaneous task than in the sequential task.

A combination of holistic and componential strategies in fraction comparisons aligns with the dual-processing framework. According to this framework, people process information by engaging two systems: a fast, automatic system (Type 1) and a slow, controlled system (Type 2) (Evans, 2008). As proposed by Van Hoof and colleagues (Van Hoof et al., 2020), the automatic system may process fraction components, while the controlled system may process the holistic magnitude of the fractions.

When solving the comparison tasks, our participants may have concurrently engaged both processing systems, leading to competition between them. This competition may explain the interaction between distance and congruency. In trials involving near distances, comparing the holistic magnitudes may require greater cognitive effort, slowing the controlled system. As a result, the automatic system may become more dominant, leading to componential processing, which is reflected in a strong congruency effect. In contrast, comparing fractions separated by far distances may require less cognitive effort, allowing the controlled system to play a greater role, increasing holistic processing and reducing the congruency effect.

Difference in task format related to stimulus presentation timing may have created differences across the congruency and distance manipulations, which may explain the interactions between task format and distance and congruency effects. As shown in a series of experiments conducted by Van Hoof and colleagues (Van Hoof et al., 2020), the automatic system is more likely to dominate in tasks with time pressure. As participants were presented with both fractions concurrently in the simultaneous task, they had a more limited time window to process them than in the sequential task. This time pressure in the simultaneous task may have forced a greater reliance on the automatic system, leading to a stronger congruency effect, particularly in near distances. In contrast, participants had an interval between the presentation of the first and second fraction in the sequential task. This additional time may have supported the engagement of the controlled system, thereby reducing the congruency effect in this task format.

While concurrent engagement of an automatic and a controlled system may explain our findings, an alternative interpretation should also be considered. The linear mixed model showed that the odds of a correct response were higher in the simultaneous task than in the sequential task. Therefore, the differences in distance and congruency effects across task formats may stem from variations in task difficulty. However, participants' mean accuracy rates in the simultaneous and sequential tasks were highly similar (93% mean accuracy in the sequential task and 94% mean in the simultaneous task). Furthermore, the same trial list was used in both tasks. Therefore, the interactions between task format, congruency, and distance are more likely explained by variations in holistic and componential strategies than task difficulty alone.

Overall, our findings align with prior studies showing that sequential and simultaneous tasks may elicit distinct strategies in number comparison tasks (Ganor-Stern et al., 2009; Mou et al., 2024; Zhang & Wang, 2005). Therefore, these task formats should not be used interchangeably. For instance, researchers interested in componential fraction processing and the congruency effect may consider prioritizing simultaneous tasks, whereas sequential tasks may be more suited to capturing holistic processing. Future studies should investigate how these tasks, and componential and holistic processing, relate to fraction comparisons performed in naturalistic settings, where people may not experience time pressure.

As this study focused only on participants' accuracy in the sequential and simultaneous tasks, future research should analyze how findings replicate with response time as the outcome. Further, since our participants were undergraduate students, future studies should analyze how results replicate to more diverse samples, including developmental samples and adults without a college degree.

To better understand how task format influences fraction comparisons, it is also important to explore the psychometric properties of simultaneous and sequential tasks. In the sequential task, participants must retain the first fraction in memory in order to compare it to the second, suggesting that the task may also engage working memory. In contrast, the simultaneous task presents both fractions at once, which may require participants to inhibit componential strategies, implicating inhibitory control. Future studies should investigate the construct validity of these task formats and statistically control for individual differences in working memory and inhibitory control.

Studies controlling possible correlations between holistic distance between the fractions and the distance between their components are also needed. In particular, studies with larger sample sizes should investigate interactions between the distance between numerators, distance between denominators, holistic distance, congruency, and task format. Finally, in this study, we only examined componential strategies by including trials where the magnitude of the fraction components was either congruent or incongruent with the holistic fraction magnitude. However, participants may also have engaged in other componential strategies, such as the gap strategy (i.e., identifying the difference between the numerator and denominator of each fraction, and comparing the differences; Morales et al., 2020; Pearn & Stephens, 2004). Future studies should also explore how task versions influence the use of various componential strategies.

In conclusion, this study examined how sequential and simultaneous task formats influenced distance and congruency effects in fraction comparisons. Results showed a robust distance effect modulated by the holistic distance between the fractions. However, the congruency effect varied across distances and task formats. The findings suggest that participants engage both holistic and componential strategies when solving fraction comparisons, and that sequential and simultaneous tasks should not be used interchangeably when these effects are analyzed.

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