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Incongruity in fraction verification elicits N270 and P300 ERP effects

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ABSTRACT

Understanding how the numerical magnitudes of fractions are accessed is a topic of major interest in numerical cognition and mathematics education. Only a few studies have investigated fraction processing using EEG methods. In the present study, 24 adult participants completed a fraction magnitude verification task while EEGs were recorded. Similar to other arithmetic verification tasks, behavioral results show increased response times to validate mismatching magnitudes compared to matching ones. ERP results show an early frontal N270 component to mismatching trials and a late parietal P300 component during matching trials. These ERP results highlight that participants treat matching fractions as targets and suggest that additional cognitive resources are needed to process mismatching targets. These results provide evidence that fractions processing shares a similar neurocognitive process as those observed during the processing of arithmetic operations and open the door to further explore fraction processing using ERP methods.

1. Incongruity in fraction verification elicits N270 and P300 ERP effects

Research on the development of mathematical abilities has highlighted the understanding of fractions as a key component of mathematics achievement (Siegler et al., 2013). Fraction knowledge is predictive of overall mathematics achievement (Siegler et al., 2012) and might underlie the ability to develop understanding of concepts needed for higher level mathematics such as algebra (Booth and Newton, 2012). However, fractions remain one of the least understood topics by elementary school students (National Mathematics Advisory Panel, 2008). Furthermore, misconceptions about fractions are carried to high school and even college (Vosniadou and Vamvakoussi, 2006).

The symbolic structure of fractions is an aspect that contributes to the observed difficulties with learning fractions. Understanding the bipartite representation of fractions in the quotient form *a/b* is crucial for accessing the numerical information of fractions. One study found that in college students, when conducting magnitude comparison tasks, this bipartite structure of fractions imposed a higher processing burden than similar magnitude comparisons with numbers such as decimals or 3-digit integers (DeWolf et al., 2014). The fact that this bipartite representation is not intuitive also accounts for errors that children make when learning fractions. One repeated difficulty children manifest is the inability to perceive fractions' numerical magnitude and to fixate instead on the numerator or denominator components as separate whole numbers (Zhang et al., 2014). The misapplication of whole number rules and procedures to fractions has been called the "whole number bias" (Zhou and Ni, 2005).

Researchers have turned to study numerically fluent adults to understand how they overcome the whole number bias and whether they compare fractions by accessing the magnitude of the whole fraction (holistic processing) or by attending to the components separately (componential processing). A numerical distance effect (NDE), the increase of response time as the numerical distance between two numbers being compared decreases (Moyer and Landauer, 1967), has been a primary tool used in these fraction studies. The response time of a fraction matching task can reflect either a numerical distance between the magnitude of a fraction and a target or a numerical distance effect between components of the two fractions being compared, thus discerning whether a componential or holistic comparison has been made. One of the first studies to inquire into strategy use in fraction processing provided evidence of componential processing, instead of holistic magnitude, by showing a NDE between the denominators of unit fractions (those with a 1 as numerator) being compared to the target 1/5 fraction (Bonato et al., 2007). However, more recent studies have highlighted how the nature of the stimuli, such as the presence of unit fractions, can influence whether a componential or holistic comparison strategy is used (Toomarian and Hubbard, 2017; Zhang et al., 2014).

The many ways fractions magnitudes can be represented makes controlling for the structure of the stimulus key to interpret

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experimental results. To better understand the effect various stimuli have on fraction comparison tasks, two studies structured stimulus to either share a numerator (2/5 vs. 2/7), a denominator (2/3 vs. 5/3), or have no common components (5/7 vs. 2/9) (Meert, Grégoire and Noël, 2010a, 2010b). These studies concluded that there was componential processing when the denominators were shared but holistic processing when the numerators were shared, suggesting a "hybrid" strategy. A study by Sprute and Temple (2011) also limited componential strategies by restricting shared components across the fractions being compared and found a magnitude NDE, suggesting the magnitude of the whole fraction was being processed.

Beyond using full componential or holistic processing strategies, adult participants have the option of using generalized strategies for processing fractions depending on task demands. Ganor-Stern et al. (2011) observed such context dependent use of either componential or holistic strategy in a fraction matching task. Another study looking at trial by trial strategy use in fraction magnitude comparisons also showed that the strategy used is dependent on stimuli, task, and level of expertise (Fazio et al., 2016). Understanding the domain-general abilities at play during these successful fraction comparison strategies is key for developing interventions that help children grasp fractions early on.

One relevant domain-general capacity in processing fractions is inhibitory control. Studies using interference suppression and response inhibition indicate that children are more susceptible to interference than adults due to children's developing executive functions (Bunge et al., 2002; Schroeter et al., 2004). Gómez et al. (2015) showed that in 5th, 6th, and 7th grade children, higher levels of inhibition predict fraction comparison proficiency and general math achievement. Another study found that 10 and 12 year-olds, like adults, were able to compare fractions through their magnitude (holistically) but they were susceptible (as seen in longer response times) to interference from shared components between the two fractions being compared (Meert et al., 2010a). Inhibitory control has been shown is needed to compare fractions in both adolescents and adults (Rossi et al., 2019). DeWolf and Vosniadou (2015) also concluded that the componential aspects of fractions might interfere with accessing the overall magnitude of fractions when the fractions compared are small. This last study suggested there is an on-line magnitude calculation that emerges out of a ratio estimation of the fraction components rather than the retrieval of the magnitude from long-term memory.

Electrophysiology measures can complement behavioral measures and are particularly suitable for exploring cognitive process such as interference of fraction components during fraction processing, with high temporal resolution. One EEG study by Zhang et al. (2012) found proportional P300 component amplitude to the numerical distance between unit fractions (e.g. 1/4, 1/9, etc.) and a 1/5 target (a simple condition). The authors concluded that this finding demonstrated evidence of componential processing. In the same study, a complex condition in which unit fractions and decimals were compared to the 1/5 target did not produce similar results. The complex condition also showed longer latency and more negative amplitude for the N2 component, over frontal electrodes, than the simple condition, suggesting a more taxing cognitive demand. However, the comparison of unit fractions to 1/5, another unit fraction, is likely to force a componential processing strategy or reliance on denominators alone, which does not necessitate processing the magnitudes of the whole fraction. Additionally, it is not clear whether the patterns observed in the complex condition come from the implementation of a different strategy or from the contextual interference of switching between fractions and decimals. Therefore, a different task structure is needed to evaluate the role that components play in making fraction comparisons.

The order of presentation (simultaneous or sequential) as well as the structure of numerical stimuli (e.g., double digits, quotient form, decimal, etc.) can influence both behavioral and ERP results. Behavioral studies requiring the comparison of two-digit numbers have shown a unit-decade compatibility effect, where the compatibility of tens and units across simultaneously presented number pairs interfere with overall processing (e.g., it is harder to compare 27 and 63, than 23 and 67) (Nuerk et al., 2001). Presenting numbers serially, instead of simultaneously, can reduce the unit-decade compatibility effect (Zhou et al., 2008). Serial presentation also helps to process numbers holistically (Ganor-Stern et al., 2009) and limit potential eye movements that would arise from looking at numerators and denominators across two simultaneously presented fractions. Thus, serial presentation of similar numbers guarantees that the comparison between a probe and a target is done on the basis of magnitude alone. A well-established ERP paradigm in the study of arithmetic with this structure is the arithmetic verification task.

ERP arithmetic verification studies have observed amplitude differences around 400 ms when the evoked potential of incongruous trials (e.g. $7 \times 4 = 26$) is compared to congruent ones (e.g. $7 \times 4 = 28$) (Niedeggen et al., 1999; Niedeggen and Rösler, 1999). In these studies, correct solutions elicit ERPs with higher amplitude positivity than incorrect solutions around 200–400 ms. This evoked potential difference was interpreted and named the arithmetic N400 (Jost et al., 2004). More recent studies have argued that the ERP pattern observed in arithmetic verification tasks is functionally and morphologically different than a N400 response (see, e.g., Dickson et al., 2018; Dickson and Federmeier, 2017; Dickson and Wicha, 2019; Jasinski and Coch, 2012; Wicha et al., 2018). Instead, the observed effect is interpreted as the amalgamation of an early frontal negative component (N270) to mismatching responses (Jasinski and Coch, 2012) and a later parietal positive component (P300/LPC) to matching responses (Dickson and Wicha, 2019). Rather than the incorrect answer eliciting a negative amplitude around 300–400 ms, the ERP studies discussed above interpreted the ERP effects around 300–400 ms as a P300 component driven by the identification of the correct target answer.

Other studies have also used the N270 and P300 components to explore processing differences in arithmetic verification. Multiple studies have observed the N270 when processing incorrect solutions in addition verification tasks (Núñez-Peña and Escera, 2007; Núñez-Peña and Honrubia-Serrano, 2004; Núñez-Peña and Suárez-Pellicioni, 2012; Szűcs and Csépe, 2005; Szűcs and Csépe, 2004). Additionally, analysis of different incorrect solutions has shown that more obviously incorrect solutions, those that are more easily categorized as incorrect, elicit a larger P300 amplitude than solutions requiring additional steps to be categorized as incorrect. This effect has been observed in table-relatedness (Dickson and Federmeier, 2017), decade-consistency (Domahs et al., 2007), problem-size (Jost et al., 2004), and in numerical split effects (Núñez-Peña and Escera, 2007). Such P300 effects are consistent with the general interpretation of the P300 component in numerical studies as reflecting difficulty in categorizing stimuli, the easier the categorization the larger the P300 (Dickson and Wicha, 2019). Furthermore, these P300 effects are sometimes observed in conjunction with the late positive component (LPC) and studied as an LPC/P3b component (Núñez-Peña and Suárez-Pellicioni, 2012; Wang et al., 2000). Verification paradigms focusing on N270 and P300/LPC, although prevalent in studies of addition and multiplication, have not yet been applied to the study of fraction processing. Given these studies of numerical processing, the N270 and P300 are relevant tools to study the processing of fraction magnitudes.

In the present study, we investigated whether a fraction magnitude equivalence verification task would show N270 and P300 effects, similar to arithmetic verification tasks in the literature. Participants judged the magnitude equivalence of two sequentially presented fractions (a probe and a target) during EEG recording. We focused our analysis on the N270 and P300 components. Following the discussion above, more negative amplitudes in the N270 time window are predicted for mismatching fractions. An N270 component in mismatching fractions would highlight that fraction magnitude incongruence elicits conflict processing which would be accompanied by increased response times. More positive amplitudes in the P300 time window are also predicted for matching fractions. The presence of a P300 across matching fractions would mean that verifying sequentially presented fractions is done by accessing the magnitude of the probe fraction whether this is done by reduction, calculation, or retrieval.

2. Method

2.1. Participants

The research was approved by the Institutional Review Board of The University of Alabama (IRB # 15-OR-314-R2). 25 right-handed, native English-speaking undergraduate students (15 female, $M = 20.7$ years, $SD = 5.31$) with no history of neurological disorders, brain injuries, or developmental disabilities were recruited from the University of Alabama to participate in this experiment. 1 participant was excluded due to a problem with the EEG system. All eligible subjects had normal or corrected-to-normal vision. Written informed consent was obtained from the participants of the study.

2.2. Experimental procedures and stimuli

Participants judged whether an initial fraction (the probe) presented on the screen had the same numerical value (magnitude) as a subsequent fraction (the target) (see Fig. 1). Participants indicated whether the target fraction was a "match" or a "mismatch"—match indicating fraction equivalence—by pressing either the right or left buttons (counterbalanced across participants), on a Logitech F310 gamepad controller. All stimuli were presented on a 15-inch LCD monitor with a 70 Hz refresh rate. Stimuli were presented on white color over a black background in Times New Roman font size 96 at a viewing distance of approximately 90 cm and a viewing angle of 3.75°.

Fractions were presented serially. The probe fraction was randomly selected from an array of the first five multiples of the unit fractions 1/2, 1/3, and 1/4. Given the range of possible strategies that college students can use to compare fractions (Fazio et al., 2016), including a range of fraction multiples for each of the three unit fractions used was expected to make it more likely that ERP averages capture magnitude comparisons. There were 15 possible probe fractions (see Table 1). The target fractions were limited to unit fractions 1/2, 1/3, and 1/4 for both the match and mismatch trials. Each of the three targets appeared equally frequent (33% of the time), half of the time as a match and half the time as a mismatch for the two other magnitudes.

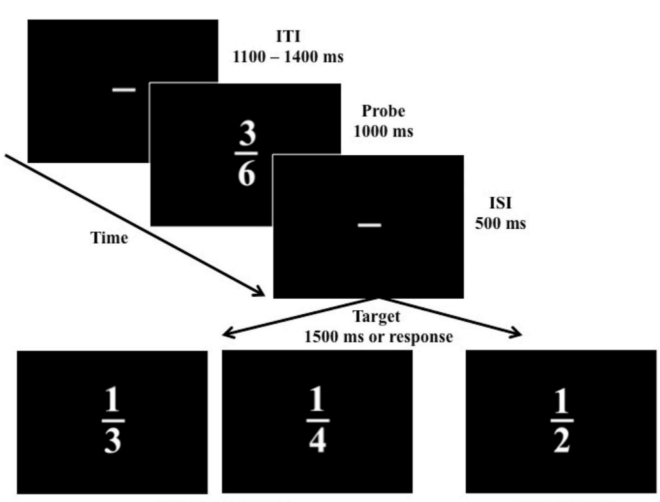

Fig. 1. Experimental progression showing the inter trial interval (ITI) shown for 1100 ms plus a 0–300 ms jitter, the probe shown for 1 s, the inter stimulus interval (ISI) shown for 500 ms, and the target presented for 1.5 s.

Table 1
Fraction stimuli per congruity condition.

Probe fraction	Target	Congruity
2/4, 3/6, 4/8, 5/10, & 6/12	1/2	Match
	1/3 or 1/4	Mismatch
2/6, 3/9, 4/12, 5/15, & 6/18	1/3	Match
	1/2 or 1/4	Mismatch
2/8, 3/12, 4/16, 5/20, & 6/24	1/4	Match
	1/2 or 1/3	Mismatch

Trials began with a fixation line centered on the screen, overlapping with the fraction bar to minimize the amount of visual difference between rest and task stimuli. Following, there was an inter trial interval (ITI) of 1100 ms plus a random jitter between 1 and 300 ms. Immediately after, the probe was presented for 1000 ms followed by an inter stimulus interval (ISI) of 500 ms. Finally, the target fraction was presented for 1500 ms or until a response was detected (see Fig. 1). ERPs with a time window of 0–800 ms were time-locked to the onset of the target fraction presentation. Trials where no response was given during target fraction presentation were excluded from the analysis (3%). Participants completed 60 randomized trials per block where each of the 15 probe fractions was repeated four times, two in matching trials and two in mismatching trials. There was a total of 10 blocks, with a total of 600 trials.

2.3. EEG acquisition and analysis

The experiment took place in a sound attenuated experiment room. Neurobs Presentation (www.neurobs.com) was used for presenting the stimulus. A Logitech F310 game controller was used as the input device. Participants used their right and left index fingers to provide responses. EEG Data was collected using a BrainVision 32 Channel ActiChamp system (www.brainvision.com), with Easy Cap recording caps using Ag/AgCl electrodes. The 32 electrodes were attached according to the international 10–20 system and referenced to Cz. BrainVision Recorder was used to record data (electrode impedance <20 kΩ, 0.5–70 Hz, 500 samples/sec). Data was downsampled to 256 Hz using a boxcar filter. A custom MATLAB script using ERPLAB (erpinfo.org/erplab/) and EEGLAB (sccn.ucsd.edu/eeglab) functions were used to analyze data. Inferential statistics were conducted with JASP (JASP Team, 2020; version 0.11.1, Amsterdam, The Netherlands).

During the analysis, the continuous EEG data was re-referenced to the average of left (TP9) and right (TP10) mastoid electrodes, high-pass filtered with 0.1 Hz half-amplitude cutoff and low pass filtered with 30 Hz half-amplitude cutoff (IIR-Butterworth, 24 dB/octave). 200 ms prestimulus period was used for baseline. Epochs were −200 ms–800 ms. All epochs were corrected to baseline. A moving window peak-to-peak threshold algorithm (for eye movements: threshold 50 μV, window size 200 ms, window step 100 ms) was implemented in all electrodes to remove artifacts. 13% of trials were rejected. Out of the total number of trials left, 4623 were match trials and 5995 were mismatch trials. Only the epochs that preceded a correct response were included in the subject-level averaged ERPs (94% of trials).

2.4. Data availability

The raw EEG and behavioral data, and the analysis scripts are publicly available in the Harvard Dataverse (https://dataverse.harvard.edu/privateurl.xhtml?token=65ebd994-5c61-4e75-84b1-75daa93e7674).

3. Results

3.1. Behavioral results

Paired samples t-tests comparing average accuracy and response times (RT) for match and mismatch were conducted. An α level of 0.05 was used to determine significance. Trials with RT outside two standard deviations of the mean were excluded, resulting in the removal of 5.1% of the trials.

There were no significant differences in accuracy between match and mismatch conditions ($t_{(23)} = -0.46$, p = .65, d = −0.09). RT results show a significant difference between match and mismatch ($t_{(23)} = -8.55$, p < .001, d = −1.75). This result is driven by slower RT for the mismatch condition (*M* = 633.84, *SD* = 133.74) as compared to the match condition (*M* = 633.84, *SD* = 133.74) (see Fig. 2).

3.2. EEG results

ANOVAs were performed on the ERP mean amplitudes and latencies of the N270 (200–300 ms) and P300 (300–450 ms) components. In order to increase the power of the analysis, the three levels of magnitude (1/2, 1/3, and 1/4) were collapsed across match and mismatch. Similar to a previous ERP study looking at the N270 and P300 components in arithmetic tasks, the analysis focused on nine electrodes (F3, Fz, F4, C3, Cz, C4, P3, Pz and P4) (Núñez-Peña and Suárez-Pellicioni, 2012). These electrodes were grouped into three regions of frontality: frontal (F3, Fz, F4), central (C3, Cz, C4), and parietal (P3, Pz, P4). Latency was calculated by computing the fractional area latency on the specified time window. Significance was determined at an α level of 0.05. Huyn-Feldt corrections were used whenever there were violations of sphericity.

3.2.1. N270

Repeated measures ANOVAs with congruence (match, mismatch) and frontality (frontal, central, parietal) factors were conducted on N270 amplitude and latency. Amplitude results showed a significant main effect of congruence, [$F_{(1, 23)} = 20.05$, p < .001, $\eta^2 = 0.042$]. Frontality was not significant, [$F_{(1.16, 26.68)} = 1.2$, p = .291, $\eta^2 = 0.01$]. There was a significant congruence × frontality interaction, [$F_{(1.28, 29.62)} = 18.83$, p < .001, $\eta^2 = 0.004$](see Fig. 3). Post-hoc pairwise comparisons to investigate the congruence × frontality interaction indicated significant differences across match and mismatch on the three levels of frontality, frontal ($t_{(23)} = 5.4$, p < .001, d = 1.1), central ($t_{(23)} = 4.5$, p < .001, d = 0.92), and parietal ($t_{(23)} = 2.73$, p = .01, d = 0.55) (see Table 2). Effect sizes indicate that match and mismatch differences in N270 amplitudes are greater over frontal electrodes (see Fig. 5).

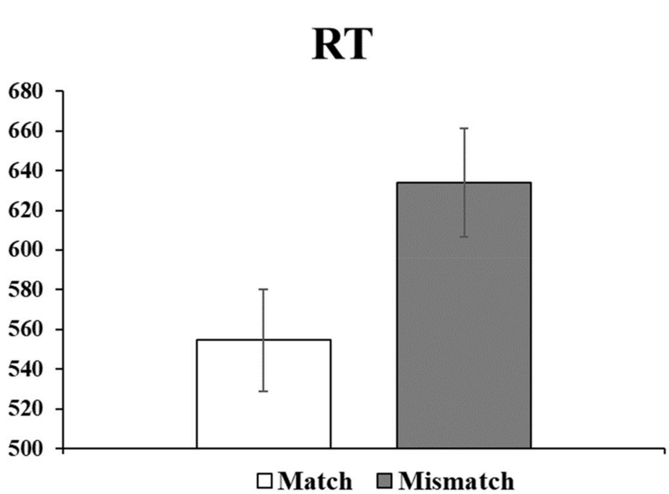

Fig. 2. Average match and mismatch RT. Error bars represent the standard errors of means.

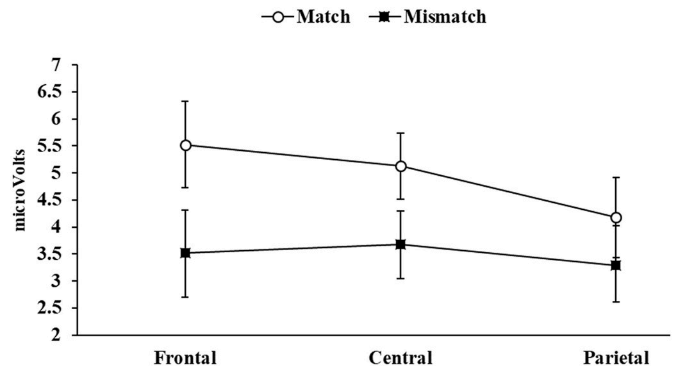

Fig. 3. Average amplitudes (μV) in the N270 (200–300 ms) time window for congruence (match, mismatch) across the three levels of frontality (frontal, central, parietal).

Table 2
Mean amplitude (microvolts) and latency values (RT) and standard deviations for the N270 and P300 time windows for match and mismatch congruence levels.

		Frontality	Match	Mismatch
N270 window (200–300 ms)	Amplitude	Frontal	5.98 (4.22)	3.04 (4.26)
		Central	6.5 (3.4)	3.87 (3.27)
		Parietal	6.2 (4)	4.12 (3.6)
	Latency	Frontal	247.504 (12.99)	246.582 (13.93)
		Central	257.704 (12.36)	246.636 (13.06)
		Parietal	257.595 (11.88)	252.116 (11.7)
P300 window (300–450 ms)	Amplitude	Frontal	7.11 (5.45)	4.8 (4.26)
		Central	10.04 (5.03)	6.65 (3.43)
		Parietal	11.15 (5.05)	7.62 (4)
	Latency	Frontal	370.98 (10.17)	386.83 (14.64)
		Central	373.8 (11.37)	388.51 (10.47)
		Parietal	375.32 (11.59)	383.25 (9.81)

N270 latency analysis revealed a significant main effect of congruence, [$F_{(1, 23)} = 5.39$, p = .029, $\eta^2 = 0.048$]. Frontality was also significant, [$F_{(1.22,28.19)} = 5.98$, p = .016, $\eta^2 = 0.05$]. There was a significant congruence × frontality interaction, [$F_{(2, 46)} = 3.47$, p = .03, $\eta^2 = 0.024$] (see Fig. 4). Post-hoc pairwise comparisons to investigate the congruence × frontality interaction indicated significant differences across match and mismatch on central areas only ($t_{(23)} = 2.84$, p = .009, d = 0.58), and not on frontal ($t_{(23)} = 0.28$, p = .78, d = 0.05) or parietal areas ($t_{(23)} = 1.94$, p = .06, d = 0.39) (see Table 2).

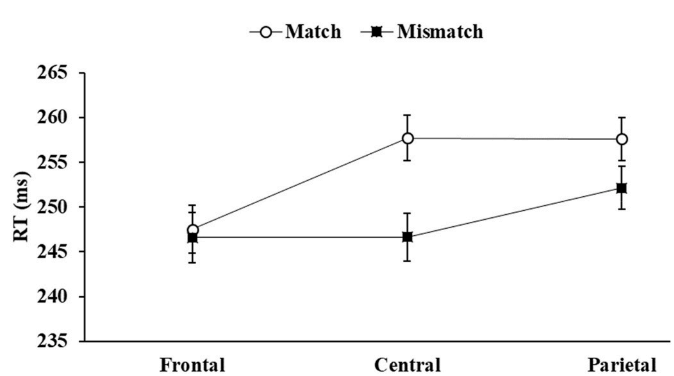

Fig. 4. N270 (200–300 ms) latency for congruence (match, mismatch) across the three levels of frontality (frontal, central, parietal).

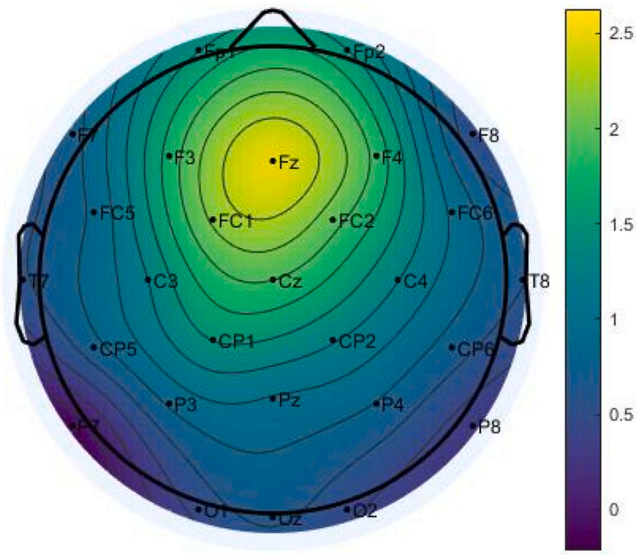

Fig. 5. Scalp distribution for the match-mismatch difference wave in the N270 (200–300 ms) time window. Bar indicates differences in microvolts (μV).

3.2.2. P300

Like with the N270 component, congruence (match, mismatch) x frontality (frontal, central, parietal) repeated measures ANOVAs were conducted on P300 amplitude and latency. P300 amplitude results indicated significant main effects of congruence, [$F_{(1,\ 23)} = 23.18$, $p < .001$, $\eta^2 = 0.097$], frontality, [$F_{(1.22,\ 28.05)} = 17.19$, $p < .001$, $\eta^2 = 0.085$], and a significant congruence × frontality interaction, [$F_{(1.32,\ 30.37)} = 13.96$, $p < .001$, $\eta^2 = 0.003$] (see Fig. 6). Post-hoc pairwise comparisons to investigate the congruence × frontality interaction indicated significant match and mismatch differences at the three levels of frontality, frontal ($t_{(23)} = 3.42$, $p < .002$, $d = 0.069$), central ($t_{(23)} = 5.15$ $p < .001$, $d = 1.05$), and parietal ($t_{(23)} = 5.54$, $p < .001$, $d = 1.13$) (see Table 2). Effect sizes of post-hoc comparison indicates the match and mismatch differences in P300 are greatest over parietal areas (see Fig. 8).

P300 latency results showed significant main effects of congruence, [$F_{(1,\ 23)} = 24.7$, $p < .001$, $\eta^2 = 0.24$]. Frontality was not significant, [$F_{(1.14,\ 34.24)} = 0.93$, $p = .37$, $\eta^2 = 0.006$]. There was no significant congruence × frontality interaction, [$F_{(1.55,\ 35.77)} = 3.52$, $p = .051$, $\eta^2 = 0.018$] (see Fig. 7).

Overall ERP results highlight the presence of a frontal N270 component in the 200–300 ms time window in the mismatch condition

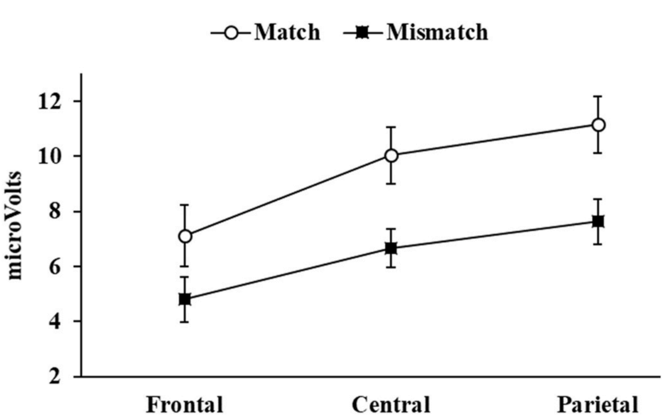

Fig. 6. Average amplitudes (μV) in the P300 (300–450 ms) time window for congruence (match, mismatch) across the three levels of frontality (frontal, central, parietal).

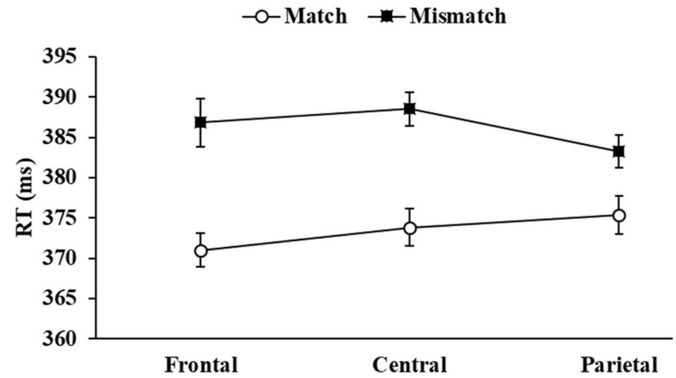

Fig. 7. P300 (300–450 ms) latency for congruence (match, mismatch) across the three levels of frontality (frontal, central, parietal).

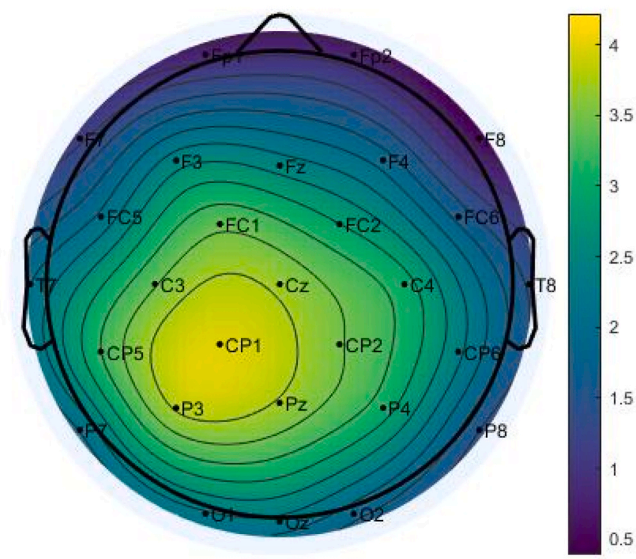

Fig. 8. Scalp distribution for match-mismatch difference waves in the P300 (300–450 ms) time window. Bar indicates differences in microvolts (μV).

and a larger parietal P300 for match condition in the 300–450 ms time window (see Fig. 9).

4. Discussion

The aim of this study was to investigate how adult participants access fraction magnitudes in real time through ERPs. The present RT results indicate mismatch trials require more time to be completed but show no differences in accuracy. ERPs results show lower amplitudes in the 200–300 ms time window to mismatching fractions and higher amplitudes in the 300–450 ms time window for matching fractions.

4.1. Effects of congruence on performance

The accuracy analysis shows no differences in performance between match and mismatch conditions despite clear differences in RT. This might be due to the adult participants performing at ceiling level in the fraction magnitude verification task. The mismatch condition, having significantly higher RT, shows a clear trend of processing costs for incongruous information. This pattern is seen in similar arithmetic tasks when incongruous stimuli are processed (Niedeggen and Rösler, 1999; Niedeggen et al., 1999).

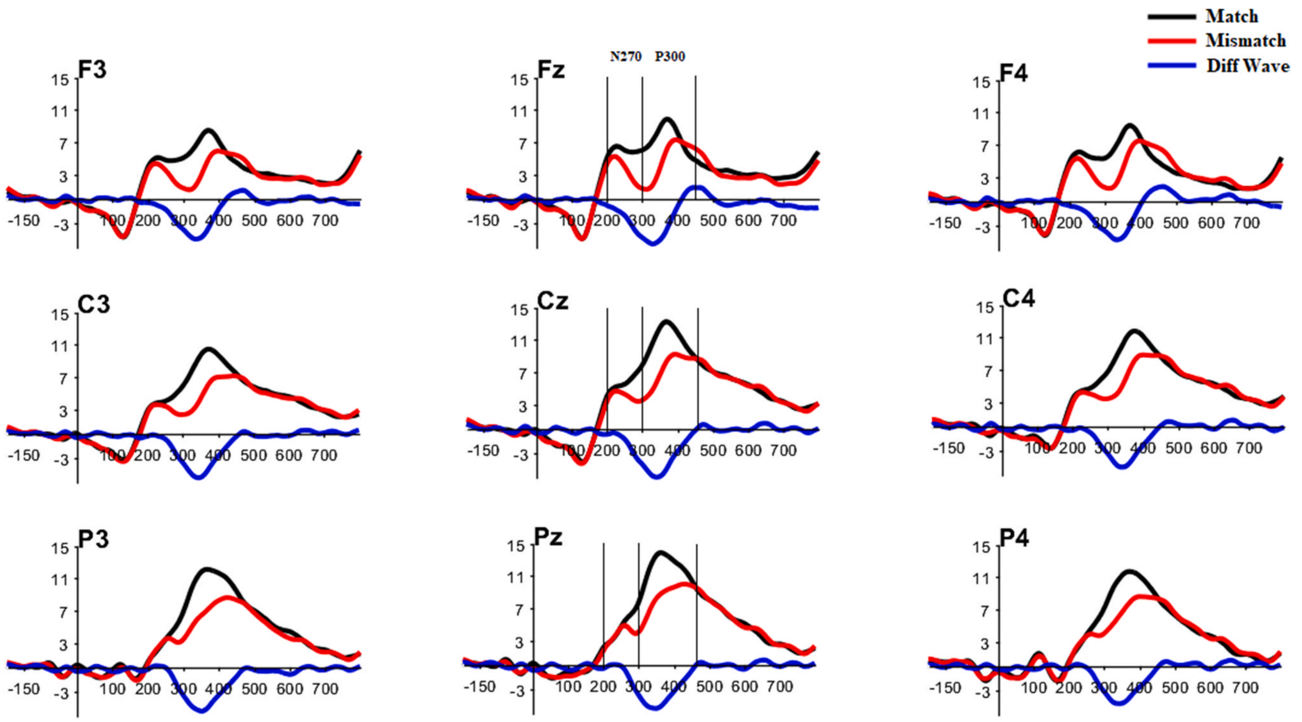

Fig. 9. Grand average ERPs for match and mismatch for electrodes in frontal (F3, Fz, F4), central (C3, Cz, C4), and parietal (P3, Pz, P4) areas. Negative is plotted down. Y axis values are in microvolts (μV). Difference waves show ERPs from matching trials subtracted from mismatching trials. The time windows for the N270 and P300 are indicated over Fz, Cz, and Pz.

4.2. Effects of congruence on ERPs

ERP results show more negative N270 amplitudes over frontal electrodes in mismatch trials compared to match trials. The N270 component has been recorded in arithmetic verification tasks after the onset of a false or incorrect answer to a preceding mental calculation (Núñez-Peña and Suárez-Pellicioni, 2012; Szűcs and Csépe, 2005). More generally, the N270 is observed during the processing of conflicting information (Jasinski and Coch, 2012; Kong et al., 2000; Lu et al., 2002; Wang et al., 2000). The presence of this N270 component when judging the equivalence of two sequentially presented fractions shows that the information from mismatching fractions begins to be processed as early as 246 ms as indicated by latency differences between match and mismatch. This difference in N270 latency was greater over central areas suggesting a fronto-central source. Additionally, the presence of this component requires the magnitude of the probe is successfully accessed and that it generates an expectation that is not met by the target. However, the N270 component could be more indicative of perceptual conflict processing between the expectation and the presented target rather than conflict due to semantics (magnitude incongruence). Further experiments are needed to ascertain the nature of the N270 in numerical processing.

There was also a P300 component over parietal electrodes when the match condition was compared to mismatch. P300 appeared earlier to match than to mismatch trials as shown in the latency differences between match and mismatch conditions. This delayed is likely due to the N270 component appearing when the conflicting information of mismatching trials is processed and can help explain the increase in RT when processing incongruous answers. This pattern of the N270 had been previously observed in arithmetic verification studies (Wang et al., 2000). This result goes along with recent interpretation of the selection of correct arithmetic answers as targets in a categorical decision (Dickson et al., 2018; Dickson and Federmeier, 2017; Dickson and Wicha, 2019; Jasinski and Coch, 2012). In order for participants to make the correct categorical decision, to indicate whether the target fraction is a match or a mismatch, they first need to access the magnitude of the target fraction. This suggests that the magnitude of the target fraction is accessed and compared to the probe by 450 ms. Furthermore, the presence of the P300 component in fraction matching shows similar processing at the ERP level than the processing of arithmetic operations such as addition and multiplication (Jasinski and Coch, 2012).

Similar to previous arithmetic verification studies (Jasinski and Coch, 2012; Núñez-Peña and Suárez-Pellicioni, 2012), we observed distinct N270 and P300 effects. In early ERP studies focusing on arithmetic processing, these effects were lumped together as a combined N400 effect, which lead to a controversy in more recent studies on whether the observed effect was indeed an N400 effect, tied to a cohesive neural source, or distinct N270 and P300 effects, showing separate latency and distribution characteristics (Dickson and Federmeier, 2017; Dickson and Wicha 2019; Jasinski and Coch, 2012). In our study, we observed a distinct frontal N270 component when mismatch trials were compared to match, and a parietal P300 component when match trials were compared to mismatch, similar to recent arithmetic processing studies (Jasinski and Coch, 2012; Núñez-Peña and Suárez-Pellicioni, 2012).

While the observed ERP effects provide evidence of access to the magnitude of the fraction, the role that fraction components might play in processing, either facilitating or impeding, is difficult to determine from the current study design. Using a different set of probe-target combinations than those used in this study can further elucidate the role that components play in fraction processing. However, the current study shows the arithmetic verification paradigm in conjunction with ERPs is a viable way to study the neurocognitive processes underlying fraction processing.

5. Conclusion

Given the many ways to represent a fraction magnitude through its multiples, understanding strategies to access the magnitude of a fraction becomes key for successful fraction processing. In accordance with the integrated theory of numerical development proposed by Siegler and Lortie-Forgues (2014), which describes numerical development being marked by broadening the set of numbers whose magnitude can be represented, it seems likely that fractions would not be integrated into the mental number line until the strategies to access their magnitudes are mastered. Thus, the many ways fractions can be represented and processed pose a unique problem for children mastering fractions and to educators seeking to develop interventions for improving outcomes in mathematics performance. Understanding the role that components play in magnitude processing, the cognitive mechanisms needed to access a fraction's magnitude, such as inhibition, and the ways to successfully develop effective processing strategies, is therefore key for improving math performance. The present study contributes to improving our understanding of fraction processing by highlighting how fraction magnitude verification shows similar ERP components as other arithmetic tasks and pointing to a shared neurocognitive process underlying magnitude processing.

Credit author statement

Brian Rivera: Conceptualization, Methodology, Software, Formal analysis, Writing – original draft. **Firat Soylu**: Supervision, Writing - Reviewing and Editing.

Ethics statement

The research was approved by the Institutional Review Board of The University of Alabama (IRB # 15-OR-314-R2). All procedures followed were in accordance with the ethical standards of the responsible committee on human experimentation (institutional and national) and with the Helsinki Declaration of 1964, as revised in 2013. Written informed consent was obtained from all individual participants involved in the study.

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