1 **Early neurophysiological signatures of multi-digit number length encoding**

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1 **Abstract**

2 The Arabic number system links number length with magnitude: longer numbers represent

3 larger values. In numerical comparisons, interference arises when physical and numerical

4 dimensions are misaligned, and processing improves with greater numerical distance. While

5 ERP studies have dissociated numerical processing effects, evidence for early encoding of

6 numerical information has been limited due to confounding visual properties. In two ERP

7 experiments, we examined whether number length influences early multi-digit number

8 processing, independent of visual size, by using scribbled line patterns to control physical

9 length. Experiment 1 (N=27) compared digit values in tie numbers (numbers with repeated

10 digits) to standard "555", ignoring number length. Experiment 2 (N=27) judged number

11 length, ignoring digit identity. Targets varied in number length and numerical distance,

12 creating congruent and incongruent conditions. ERP results revealed enhanced parieto-

13 occipital N1 negativity (~120–150 ms) for longer numbers, indicating early number length

14 encoding independent of overall visual size. Central P2p (~150–190 ms) reflected refined

15 numerical distance processing. Centro-parietal P3 (~300–360 ms) showed congruity effects

16 only when numerical magnitude was task-relevant. These findings reveal three distinct

17 processing stages: early encoding (N1), refined magnitude comparison (P2p), and conflict

18 resolution (P3). This novel neurophysiological evidence showcases the unique influence of

19 number length and numerical syntax on magnitude evaluation.

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21 Keywords: multi-digit numbers, number length, N1 component, numerical syntax.

Early neurophysiological signatures of multi-digit number length encoding

The Hindu-Arabic numerical notation we use daily presents an integrated display of quantity through both symbolic digits and their positional arrangement. This numerical system encodes information along two key dimensions: the base dimension, conveyed through the specific digit shapes (0–9), and the power dimension, represented by each digit's placement within the multi-digit number [1].

Understanding how the mind interprets this structure has led to several models of multi-digit number processing. The holistic model proposes that multi-digit numbers are represented as unified entities, similar to single digits or familiar words (e.g., [2-6]). In contrast, the decomposed model suggests that each component digit is processed independently (e.g., [7−12]). A third approach, the hybrid model, assumes that both individual digits and whole number magnitudes can be represented and activated in parallel, or compete, depending on task demands (e.g., [11,13,14]).

These models are often examined in number comparison tasks, which reveal important distinctions between processing single- and multi-digit numbers. In single-digit comparisons, both stimuli typically consist of one digit, so only their symbolic values differ. Multi-digit number comparisons, however, introduce greater complexity by requiring an understanding of numerical syntax, namely how digits combine into meaningful numbers and how multi-digit numbers break down into components (e.g., [15]). This syntax creates systematic connections between a number's physical features (digit count and overall length) and its quantitative value (e.g., [16−23]). For example, comparing numbers like 30 and 300 illustrates this numerical–physical property relationship clearly: 300 is longer visually, contains an additional symbol, and represents a value ten times greater than 30, all direct consequences of decimal place-value organization. This makes number length a reliable visual indicator when comparing numbers of different lengths.

Building on the numerical-physical link in multi-digit number comparisons, we recently proposed [21] that number comparisons involve (at least) two distinct processes that evaluate numerical magnitude and operate in parallel: a crude process that evaluates the binary question of "which is smaller/larger?", and a refined process that determines "by how much smaller/larger?". These two processes race against each other following a parallel minimum-time stopping rule, where responses can be made upon completion of the first process (e.g., [13,24−27]). While single-digit comparisons are typically too rapid for process dissociation, multi-digit number comparisons are slower due to greater syntactic complexity, potentially allowing observation of both processes. We further argued that number length provides key information for the crude process, and while decisions can be based on the crude process alone, both processes may contribute to the final response when they complete in time to influence the decision. Converging work (e.g., [28−31]) likewise shows that number length and numerical syntax strongly shape multi-digit number processing. Specifically, according to Dotan and Friedmann's [30] model, a "visual analyzer" recognizes number length during an early processing phase that includes encoding digit identities, their order, and the number's overall length.

Research on numerical processing has also identified two robust phenomena that serve as valuable tools for investigating underlying mechanisms: the distance effect and the size congruity effect. The distance effect [32] reveals faster responses when comparing numbers that are numerically further apart (e.g., comparing 2 vs. 9 is faster than 2 vs. 3). The size congruity effect (e.g., [33,34]) emerges in tasks where both numerical and physical dimensions vary, producing slower and less accurate responses for incongruent than congruent trials (e.g., 4_6 vs. 4_6, respectively). These effects occur automatically, without conscious monitoring (e.g., [35−37]) and regardless of task requirements (e.g., [33,34,38−41]). Importantly, they have been extended beyond single-digit comparisons to

multi-digit number comparisons (e.g., [23,42−46]), where number length (rather than font

size) can create congruity effects similar to the classic font size congruity effect (e.g.,

[18,20,21,23,46]).

Following extensive behavioral evidence for the distance and size congruity effects,

neurophysiological research using event-related potentials (ERPs) has provided detailed

insights into the sequential stages of number processing. Previous ERP studies have identified

specific neural patterns associated with these classic effects. The size congruity effect is

typically reflected in the P3 component, distributed over centro-parietal sites, usually

emerging around 300 ms post-stimulus onset. It is characterized by decreased P3 amplitude

and delayed latency for incongruent compared to congruent stimuli (e.g., [50−55]). The P3 is

considered a post-perceptual component, related to stimulus evaluation and categorization

processes (e.g., [56−59]).

The P3 is also sensitive to the numerical distance effect, with larger distances

associated with larger amplitudes and shorter latencies (e.g., [52,60,61]). Importantly,

however, the numerical distance effect is already observed in the P2p (second posterior

positivity) component, appearing around 200 ms post-stimulus onset, which is earlier than the

P3, over bilateral parieto-occipital sites. Localized to the parietal-occipital lobe and the

intraparietal sulcus (IPS), the P2p shows larger amplitudes for smaller than for larger

numerical distances (e.g., [60,62−66]).

Some researchers have suggested that the distance effect is already evident at an

earlier stage post-stimulus onset, namely, in the transition from the N1 to the P2p component

[63] or in the N1 component (e.g., [62,65,66]). The N1 component, usually occurring

between 130 and 200 ms post-stimulus onset, is known to be heavily influenced by the visual

properties of stimuli, such as size, luminance, and spatial frequency (e.g., [59,67]). While

some have argued that an increase in numerosity is not properly disentangled from changes in

the visual properties of non-symbolic number stimuli (e.g., [68−70]), the notion that the N1 is also affected by numerically relevant processes cannot be easily dismissed. This is because the N1 is also influenced by top-down processing (e.g., [71,72]), and has shown unique activation in the right angular gyrus and occipital-temporal regions in response to Hindu-Arabic digit stimuli (e.g., [73,74]). Recent EEG data suggest that numerosity has a unique signature in visual processing, separate from other visual properties (e.g., [75,76]), a finding supported by cross-modal evidence showing that the N1 component is modulated by preceding auditory numerosity information [77]. Together, these studies support the notion that the N1 component may be influenced by numerical processes alongside processes dedicated to encoding non-numerical visual properties.

The present study

The present study aimed to investigate the electrophysiological correlates of processing number length and the numerical value it represents. Based on the aforementioned research, consistent with the model proposed by Lozin and Pinhas [21], as well as the notion of a "visual analyzer" (e.g., [24−27]), various processes related to the numerical aspects of the stimuli may take place at different processing stages, including early ones. The high temporal resolution of ERPs provides a viable method to detect and differentiate between these processes, and to examine the electrophysiological signature of a possible distinct crude process for estimating a number's magnitude [21], separate from decoding the number's non-numerical visual properties.

Specifically, we were interested in the relative contributions of number length versus the numerical values of the individual digits. Our primary objective was to determine whether number length is encoded at the earliest stages of neurophysiological processing, specifically at the N1 component (~120-150 ms post-stimulus). To this end, we conducted two experiments with concurrent EEG and behavioral recording using different comparison tasks.

In Experiment 1, participants performed a numerical comparison task against a standard of 555, focusing solely on the digit identity while ignoring number length. In Experiment 2, participants performed a physical comparison task against a standard of 555, focusing on the number length while ignoring digit identity. In both experiments, we used tie numbers of different lengths (1, 2, 4, or 5 digits) with equalized overall visual sizes via scribbled line patterns on both sides of the stimuli (Figure 1), enabling us to isolate number length processing from overall visual size. This design created two number-length-component congruity conditions, where in congruent trials, the longer number contained the larger repeating digit (e.g., 22 vs. 555 or 88888 vs. 555), and in incongruent trials, the longer number contained the smaller repeating digit (e.g., 77 vs. 555 or 4444 vs. 555).

Based on recent empirical findings (e.g., [18,21]), we anticipated that both number lengths and digit values would be processed automatically, producing a number-length-component congruity effect with slower reaction times (RTs) for incongruent trials, and that number lengths would demonstrate greater saliency over individual digit values in multi-digit number processing. We examined later ERP components (P2p and P3) as secondary validation that our paradigm replicates established effects, but the primary focus of the present study was on early processing as reflected in the N1 component. Our sample size was determined by an a priori GLMM-based power analysis (see Methods), which achieved high power (1-β > .95 at α = .01) for the relevant main effects in each component, whereas interaction terms were treated as exploratory.

1   **Figure 1.** Illustration of trial structure, duration, and stimuli (not drawn to scale).
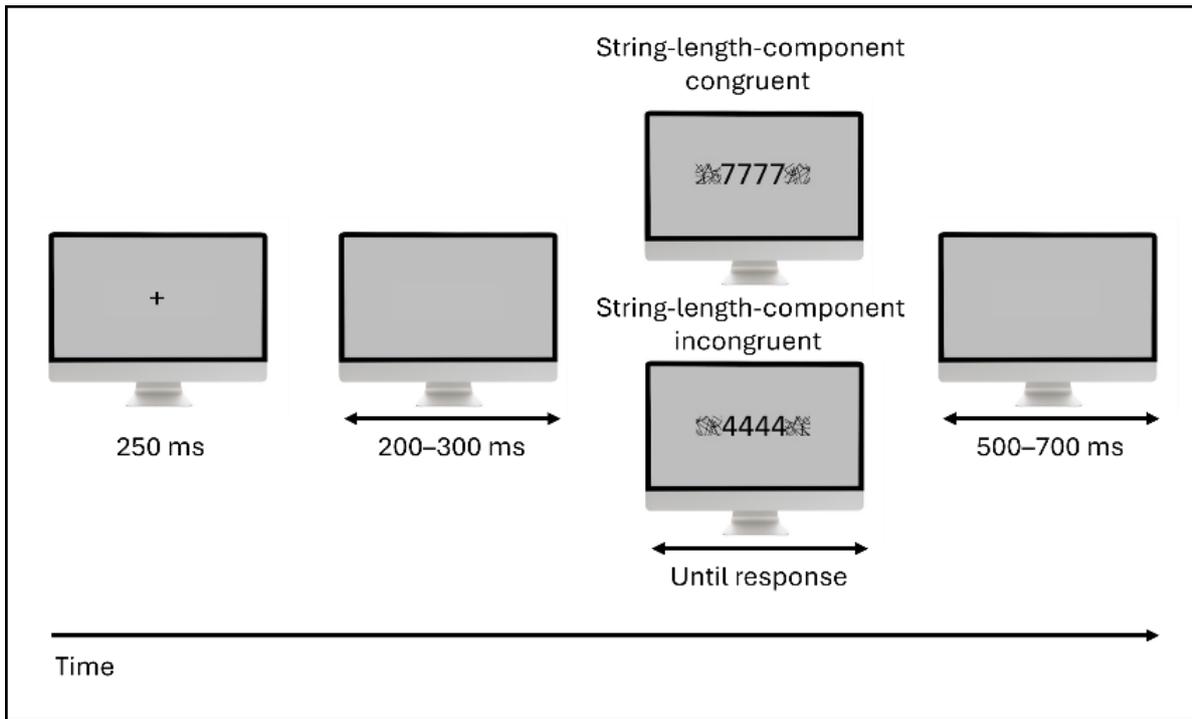
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3   *Note.* In number-length-component congruent pairs, the longer number contains the larger

4   repeating digit, while in number-length-component incongruent pairs, the longer number

5   contains the smaller repeating digit. ERPs were time-locked to the target number's onset.

6

7   **Experiment 1: Numerical Comparison Task**

8   In Experiment 1, we expected that participants would show strong interference from

9   the task-irrelevant number length dimension even when focusing solely on digit identity.

10   Behaviorally, this was predicted to manifest as slower reactions to incongruent than

11   congruent stimuli (e.g., [18,21,78−85]). Consistent with previous research (e.g.,

12   [23,34,38,40,41,43,47−49,70]) we also anticipated that the number-length-component

13   congruity effect would increase with increased number length distance, defined as the

14   difference in number length between the stimuli and the standard "555".

15   At the neural level, we expected to find ERP markers of the conflict between number

16   length and digit value, particularly in the P3 component (e.g., [50−53]), with decreased

amplitude and delayed latency for incongruent compared to congruent trials. We also anticipated effects in earlier components, specifically the P2p (e.g., [60,62−66]), which would show modulation by numerical distance, with larger amplitudes for smaller numerical distances. Lastly, we were particularly interested in examining whether the N1 component would reflect early sensitivity to number length, supporting the view that crude numerical magnitude processes occur at early processing stages, as we previously suggested [21].

Method

Participants

An a priori power analysis based on a preliminary trial with 14 participants assumed a Generalized Linear Mixed Model (GLMM) for amplitude (μV), with number-length-component congruity (congruent, incongruent) and number length distance (1, 2) as within-participants factors, componential numerical distance (1, 2, 3) and log-transformed global numerical distance (the absolute difference between the target number and the standard "555") as covariates, and participants as a random factor. Two-hundred simulations were executed in R (R Core Team, 2019) via the powerSim function of the simr package [86]. Based on the simulated results, a sample of 27 participants fulfilled prerequisites of $\alpha = .01$ and 95% power for the relevant main effects in each component.

Our power analysis was designed to detect main effects of number-length-component congruity, numerical distance, and number length distance on ERP amplitudes of the N1, P2p, and P3 components, which were the primary focus of our hypotheses. Specifically, we aimed to establish whether number length influences early processing (N1 component) and to validate that our paradigm replicated established effects at later components (P2p and P3). While we included Number-Length-Component Congruity × Number Length Distance and Number-Length-Component Congruity × Componential Numerical Distance interactions terms in our statistical models for analytical completeness, testing interaction effects was

exploratory rather than hypothesis-driven. Consequently, non-significant interactions should

be interpreted as inconclusive rather than as evidence for null effects.

Twenty-seven undergraduate psychology students (aged 19-26 years, average age

22.72 years, 21 female, 7 male, 4 left-handed, 26 native Hebrew speakers, 1 native English

speaker) from Ariel University participated in the experiment in exchange for course credit.

Participants had normal or corrected to normal eyesight and had not been diagnosed with

dyscalculia. Prior to the beginning of the experiment, participants signed an informed consent

form. The study protocol was approved by Ariel University's Ethics Committee for Non-

Clinical Human Research. All experiments were performed in accordance with relevant

ethical guidelines and regulations.

Apparatus and stimuli

The experiment was conducted on a personal computer with a 24-inch monitor. E-

Prime v3.0 software (Psychology Software Tools, Pittsburgh, PA, USA) controlled stimulus

presentation. Participants responded by pressing the "A" and "L" keys on a standard

QWERTY keyboard.

The stimuli were generated from single-digit tie numbers. Hence, numbers were

composed of the repeated digit 2, 3, 4, 6, 7 or 8 (e.g., 44, 2222). Tie numbers of various

lengths (1, 2, 4, or 5 digits) were presented with equalized visual overall size by utilizing

randomized scribbled line patterns surrounding the numbers. Importantly, the differences

between the numerical values of the displayed tie numbers and the standard "555" created

two number-length-component congruity conditions. In congruent pairs, the longer number

(either the presented number or the standard held in memory) contained the larger repeating

digit (e.g., 22 vs. 555 or 88888 vs. 555). In incongruent pairs, the longer number contained

the smaller repeating digit (e.g., 77 vs. 555 or 4444 vs. 555). The stimuli differed from the

standard in number length distance of either 1 or 2, and in componential numerical distance

of either 1 (4 vs. 5; 6 vs. 5), 2 (3 vs. 5; 7 vs. 5), or 3 (2 vs. 5; 8 vs. 5).

Stimuli were presented at the center of the monitor, approximately 60 cm from

participants' eyes. The numbers were presented in black bold Courier New font on a silver

background. The heights of all numbers were ~2.77º, and their widths were between ~1.91º

for single digit numbers, and ~9.91º for the five-digit numbers. The overall visual length

including the scribbled line patterns was a constant ~12.46º. Each tie number was paired with

5 unique scribble patterns and presented 10 times with each pattern. Thus, each tie number

appeared in 50 trials overall, for a total of 1,200 trials per participant (24 tie numbers × 5

scribble patterns × 10 repetitions).

Procedure

The task was a comparison to the standard "555". Participants were instructed to

decide if the digit identity of the displayed tie number was smaller or larger than the digit

identity in the standard "555", while ignoring the number's length. Participants sat in front of

the monitor with their index fingers on the response keys. Each trial started with the

presentation of a fixation dot at the center of the screen for 250 ms, followed by a blank

screen presented for a random duration between 200 and 300 ms, then a tie number that

remained visible until a response was made. After a response, a blank screen was presented

for a random duration between 500 and 700 ms before the next trial began.

Participants were instructed to select whether the presented digit identity was smaller

or larger than the standard as quickly and as accurately as possible. They pressed the A/L key

on the keyboard if they chose smaller/larger, respectively. A short training session of 10 trials

was completed first, followed by 15 successive blocks of 80 trials each, for a total of 1,200

trials. The trials were randomly ordered.

EEG recording and analysis

The ongoing EEG was recorded in a sound-attenuated, electrically shielded room from 64 scalp sites using the BrainVision actiCHamp Plus system (Brain Products GmbH) and BrainVision Recorder software. Two anterior channel pairs were used to detect eye blinks and eye movements. Recordings were referenced online to the left mastoid (TP9) and digitized at a 500 Hz sampling rate with a 24-bit A/D converter. Electrode impedances were maintained below 25 kΩ.

Offline, data were processed in BrainVision Analyzer 2.3.0. Data were re-referenced from the online left mastoid reference (TP9) to the average of the left and right mastoids (TP9, TP10). A 40 Hz digital low-pass filter was then applied to the data (with a 0.1 Hz high-pass filter). Ocular artifacts were corrected using ICA-based ocular correction, with automatic blink detection using the Mean Slope algorithm of Gratton et al. [87]. Then, correct trials (i.e., the ones included in the behavioral analysis) were segmented into epochs starting 200 ms before the onset of the target number to 600 ms post-stimulus. Bad channels outside the regions of interest were corrected using topographic interpolation. The resulting epochs were subjected to an automated artifact detection procedure, with epochs rejected if the difference of values within them exceeded 140 µV. Artifact-free trials were averaged to experimental conditions of interest (i.e., all number-length-component congruity × pair type × distance combinations) for each participant and baseline corrected to the average amplitude from -200 to 0 ms before stimulus onset. On average, 1,102.52 (SD = 65.40) epochs were retained for each participant for the analyses. Table 1 presents an overview of the mean number of retained epochs per participant and condition of interest. Finally, grand averages and topographical maps across all participants were generated.

Table 1. Experiment 1 – Mean retained number of epochs per participant and condition.

Factor	Level	Mean	SD
Number length distance	1	552.70	32.62
Number length distance	2	549.78	34.59
Componential numerical distance	1	360.37	25.36
Componential numerical distance	2	369.67	21.85
Componential numerical distance	3	372.44	21.49
Number-length-component congruity	Congruent	554.93	31.08
Number-length-component congruity	Incongruent	547.56	36.43

2

3   The selection of ERP components and latencies for analysis was guided by previous

4   research (e.g., [50−55,59,62,63,65−67]) and confirmed by visual inspection of the grand-

5   average waveforms and topographical maps across participants. We identified three time

6   windows corresponding to the three observed ERP components of interest: N1 (covering the

7   first posterior negative-going deflection that follows the P1; 120–150 ms, Oz, O1, POz, PO3),

8   P2p (covering the second posterior positive-going deflection; 150–190 ms, FC1, FCz, FC2,

9   C1, Cz, C2, CP1, CPz, CP2), and P3 (covering an extended positive-going deflection over

10   both centro-parietal and posterior sites; 300–360 ms, C1, Cz, C2, CP1, CPz, CP2, P1, Pz, P2).

11   SPSS software (Version 26.0, International Business Machines Corporation, 2022)

12   was used for all data analyses. A GLMM was conducted on mean amplitudes (μV) for each

13   component separately (i.e., N1, P2p, P3), with number-length-component congruity

14   (congruent, incongruent) and number length distance (1, 2) as within-participants factors,

15   componential numerical distance (1, 2, 3) and log-transformed global numerical distance as

16   covariates, and participants as a random factor. For the P3 component, an additional latency

17   analysis was conducted, employing the 50% fractional area latency measure, which calculates

18   the total area under the curve within a 250–450 ms post-stimulus time window to identify the

19   time point dividing the area into equal halves.

20   It is important to note that while our figures present grand-averaged ERP waveforms

21   and topographical distributions without adjusting for covariates (particularly log-transformed

global numerical distance), our reported statistical findings derive from comprehensive

GLMMs that account for these factors. This methodological distinction occasionally creates

apparent discrepancies between the visualizations and the statistical outcomes, particularly

when examining effects that share variance with global numerical distance. Conventional

ERP visualizations cannot graphically incorporate covariate controls implemented in

statistical models. Our GLMM approach provides a more nuanced assessment by accounting

for shared variance between predictors, thus revealing effects that might otherwise remain

obscured in grand-averaged waveforms. This approach isolates the unique contribution of

each factor while statistically controlling for others that influence ERP components. In

specific cases where including global numerical distance substantially alters the interpretation

of a key effect, we have noted this explicitly in the text.

Behavioral analysis

A GLMM was conducted on RTs with number-length-component congruity

(congruent, incongruent) and number length distance (1, 2) as within-participants factors,

componential numerical distance (1, 2, 3) and log-transformed global numerical distance as

covariates, and participants as a random factor. We examined the main effects of number-

length-component congruity and number length distance, and the two-way interaction of

Number-Length-Component Congruity × Number Length Distance. The two-way and three-

way interactions that included componential numerical distance were not included in the

model due to multicollinearity with the main effect of componential numerical distance. All

reported chi-square results are from Wald chi-square tests, which assess the significance of

predictors in the model. All reported means are estimated marginal means, which represent

the predicted mean values from the GLMM while controlling for the effects of covariates and

accounting for the mixed-effects structure. These estimated marginal means provide model-

1   adjusted estimates that isolate the effects of the experimental factors of interest while holding

2   covariates at their mean values.

3   In all GLMM analyses, we report for each fixed effect the estimated unstandardized

4   regression coefficient (b) and its 95% Wald confidence interval, in addition to the

5   corresponding Wald χ^2 statistic and p-value. The regression coefficient b quantifies the size

6   and direction of the effect on the original scale of the dependent variable (milliseconds for RT

7   and latency, microvolts for ERP amplitudes). Thus, b provides an interpretable effect size (for

8   example, the expected change in RT in ms, or change in ERP amplitude in µV, associated

9   with a one-unit change in the predictor). The 95% confidence interval around b indicates the

10   range of effect sizes that are most compatible with the data; effects whose 95% CI does not

11   include 0 are interpreted as reliably non-zero. Evaluating b on the original measurement scale

12   allows us to gauge whether effects are small, medium, or large in practical terms, and

13   complements the inferential information provided by χ^2 statistics and p-values.

14   The study design and analyses were not preregistered.

15   **Results**

16 *Behavioral analysis*

17   The main effect of number length distance was significant, $\chi^2(1) = 5.33$, $p = .021$, $b =$

18   -5.03, 95% CI [-9.30, -0.76], reflecting faster responses for trials with number length distance

19   of 1 (505 ms) compared to those with distance of 2 (510 ms). The main effect of number-

20   length-component congruity was also significant, $\chi^2(1) = 17.61$, $p < .001$, $b = 8.71$, 95% CI

21   [4.64, 12.78], reflecting faster responses for congruent (504 ms) compared to incongruent

22   (512 ms) trials. In addition, both main effects of componential numerical distance, $\chi^2(2) =$

23   231.30, $p < .001$, $b = -19.17$, 95% CI [-21.64, -16.70] and log-transformed global numerical

24   distance, $\chi^2(1) = 35.61$, $p < .001$, $b = -7.92$, 95% CI [-10.51, -5.32], were significant. Finally,

25   the Number-Length-Component Congruity × Number Length Distance interaction was

1 significant, $\chi^2(1) = 5.75$, $p = .016$, $b = -9.86$, 95% CI [-17.92, -1.80] (Figure 2). Follow-up

2 pairwise comparisons of estimated marginal means showed that the number-length-

3 component congruity effect was significant at number length distance 2 (*mean difference* =

4 13.64 ms, SE = 2.92, 95% CI [7.92, 19.37], $p < .001$), but not 1 (*mean difference* = 3.78 ms,

5 SE = 2.92, 95% CI [-1.94, 9.51], $p = .195$).

6

7 *Figure 2.* Experiment 1 – Estimated marginal mean RT as a function of number-length-

8 component congruity and number length distance.
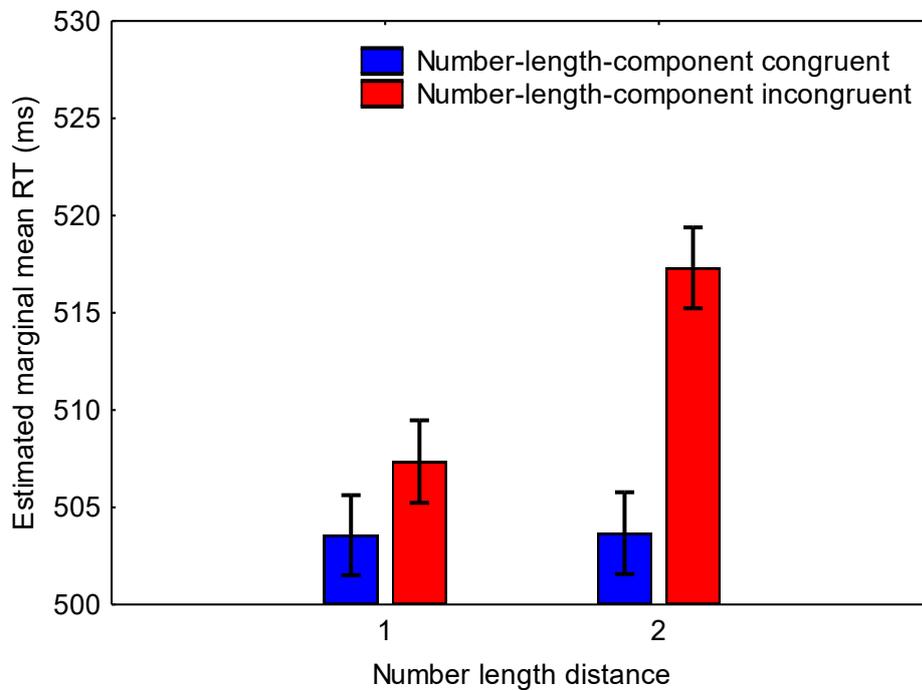
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10 *Note.* Vertical bars denote +/- standard errors.

11

12 ***ERP analysis***

13 ***N1 component (120−150 ms; electrodes: Oz, O1, POz, PO3).*** A significant main

14 effect of number length distance was observed, $\chi^2(1) = 120.33$, $p < .001$, $b = 1.13$, 95% CI

15 [0.93, 1.33], showing greater negativity for distance 2 (-1.25 μV) than for distance 1 (-0.13

16 μV) (Figure 3). The main effects of number-length-component congruity, $\chi^2(1) = 3.11$, p

16

1 = .078, $b = 0.17$, 95% CI [-0.02, 0.36], and componential numerical distance, $\chi^2(1) = 0.19$, p

2 = .659, $b = 0.03$, 95% CI [-0.09, 0.14], did not reach significance, while the main effect of

3 log-transformed global numerical distance was significant, $\chi^2(1) = 241.40$, $p < .001$, $b = 0.97$,

4 95% CI [0.85, 1.10]. Lastly, the interaction between number-length-component congruity and

5 number length distance was not significant, $\chi^2(1) = 1.44$, $p = .231$, $b = 0.23$, 95% CI [-0.15,

6 0.61].

7

8 *Figure 3.* Experiment 1 – ERP traces and topographic distribution for the N1 component.
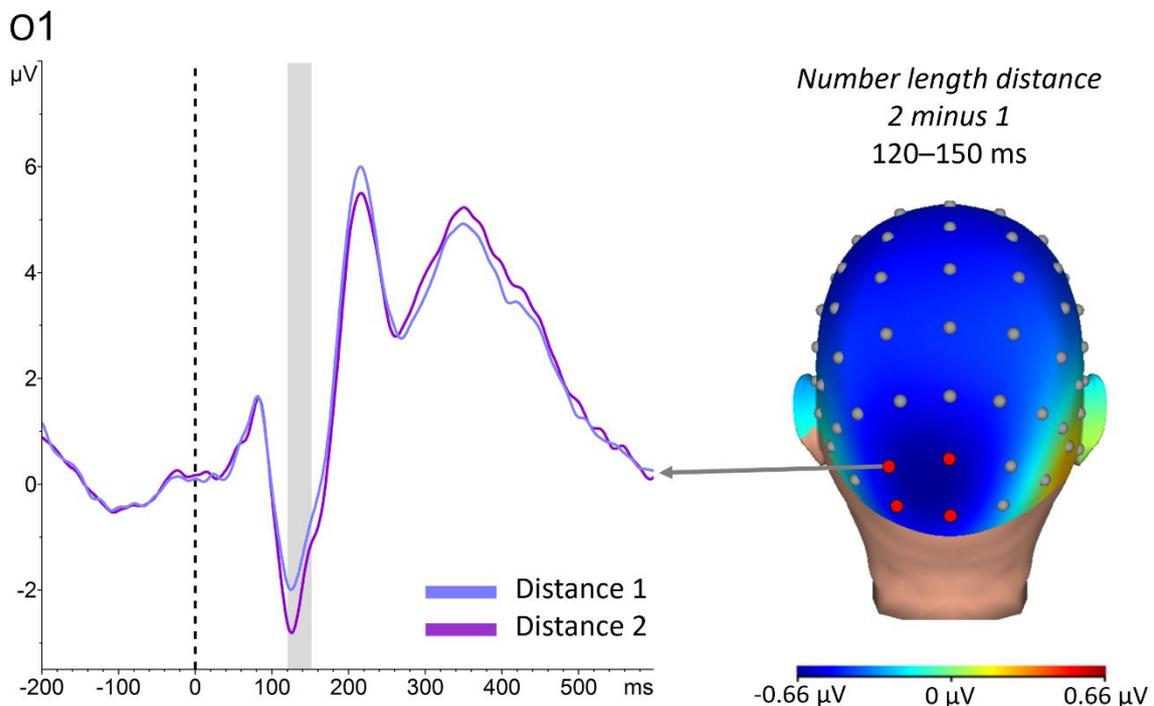

11 ***P2p component (150−190 ms; electrodes: FC1, FCz, FC2, C1, Cz, C2, CP1, CPz,***

12 ***CP2).*** A significant main effect of number length distance emerged, $\chi^2(1) = 19.15$, $p < .001$, b

13 = 0.55, 95% CI [0.30, 0.79], with greater positivity for distance 1 (3.90 µV) compared to

14 distance 2 (3.36 µV). The main effect of number-length-component congruity was not

15 significant, $\chi^2(1) = 0.20$, $p = .654$, $b = 0.05$, 95% CI [-0.18, 0.29]. As expected, the effects of

16 componential numerical distance, $\chi^2(1) = 58.42$, $p < .001$, $b = -0.55$, 95% CI [-0.69, -0.41]

1 (Figure 4), and log-transformed global numerical distance, $\chi^2(1) = 33.03$, $p < .001$, $b = 0.44$,

2 95% CI [0.29, 0.59], were both significant. In addition, the Number-Length-Component

3 Congruity × Number Length Distance interaction was not significant, $\chi^2(1) = 0.01$, $p = .941$, b

4 = -0.02, 95% CI [-0.48, 0.44].

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6 *Figure 4.* Experiment 1 – ERP traces and topographic distribution for the P2p component.
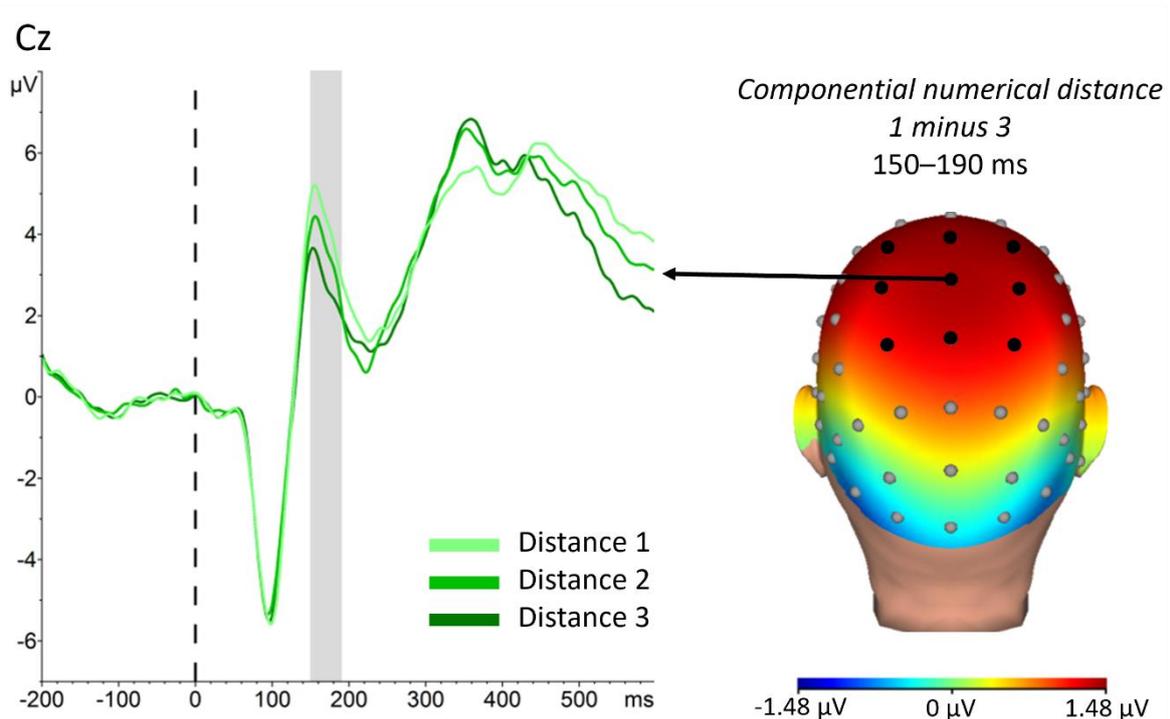

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9 ***P3 component (300−360 ms; electrodes: C1, Cz, C2, CP1, CPz, CP2, P1, Pz, P2).***

10 P3 mean amplitude analysis revealed a significant main effect of number length distance,

11 $\chi^2(1) = 9.97$, $p = .002$, $b = 0.45$, 95% CI [0.17, 0.72], indicating greater positivity for distance

12 1 (6.38 µV) than for distance 2 (5.94 µV). A significant main effect of number-length-

13 component congruity emerged, $\chi^2(1) = 8.90$, $p = .003$, $b = -0.40$, 95% CI [-0.66, -0.14],

14 showing greater centro-parietal positivity for congruent (6.36 µV) compared to incongruent

15 (5.96 µV) trials (Figure 5). Additionally, there was a significant main effect of componential

16 numerical distance, $\chi^2(1) = 12.92$, $p < .001$, $b = 0.29$, 95% CI [0.13, 0.45]. The interaction

1 between number-length-component congruity and number length distance was not

2 significant, $\chi^2(1) = 0.49$, $p = .485$, $b = 0.19$, 95% CI [-0.34, 0.71].

3

4 **_Figure 5._** Experiment 1 – ERP traces and topographic distribution for the P3 component.
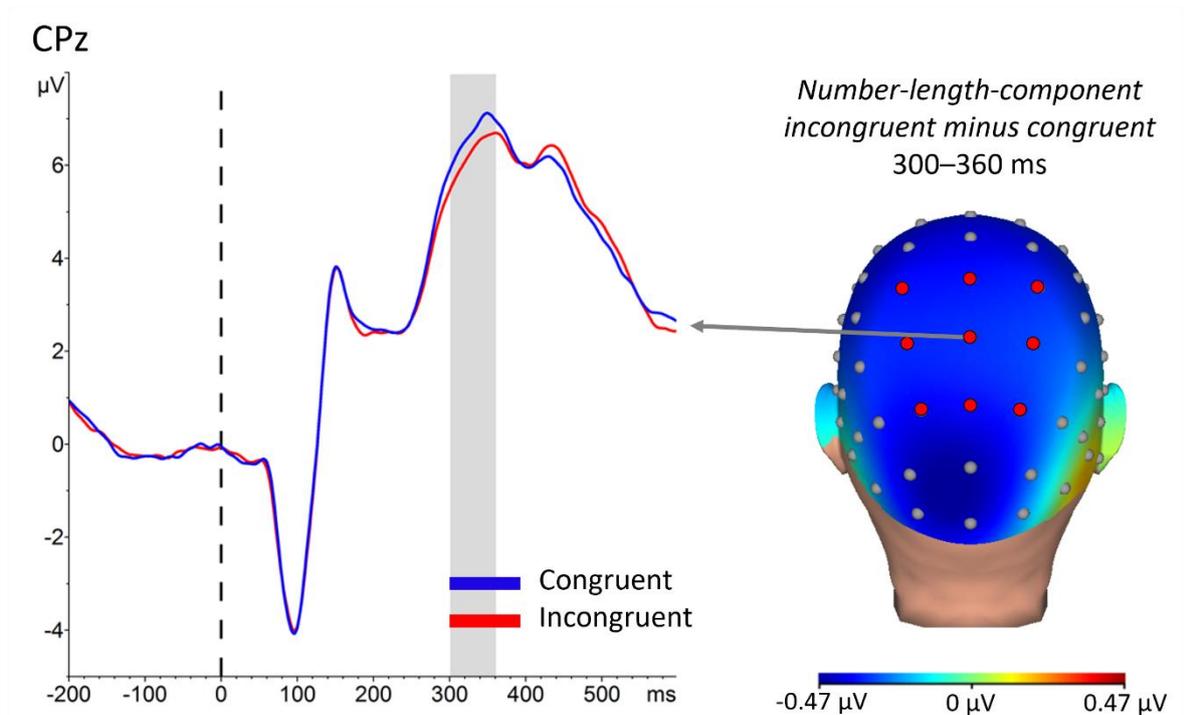
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7   Importantly, when we included log-transformed global numerical distance as an

8 additional covariate in the model, the number-length-component congruity effect became

9 non-significant, $\chi^2(1) = 2.99$, $p = .084$, $b = -0.23$, 95% CI [-0.50, 0.03]. In this full model, log-

10 transformed global numerical distance was significant, $\chi^2(1) = 77.29$, $p < .001$, $b = 0.76$, 95%

11 CI [0.59, 0.93]. Diagnostic analyses ruled out multicollinearity and loss of power as

12 explanations for this pattern, and confirmed that the model including log-transformed global

13 numerical distance provided superior fit (see Supplementary Materials, Experiment 1). The

14 reduction in the number-length-component congruity effect reflects shared variance: log-

15 transformed global numerical distance is jointly determined by digit identity and number

16 length, and thus congruent and incongruent trials cluster systematically along the global

19

distance dimension as detailed in the supplementary analyses. For clarity, the number-length-component congruity effect reported above is from the model excluding log-transformed global numerical distance, while all other P3 amplitude effects are from the model including this covariate.

An additional latency analysis conducted for the P3 component revealed that the main effect of number length distance was not significant, $\chi^2(1) = 1.35$, $p = .246$, $b = 0.35$, 95% CI [-0.94, 0.24]. In contrast, the main effect of number-length-component congruity was significant, $\chi^2(1) = 9.01$, $p = .003$, $b = 0.86$, 95% CI [0.30, 1.43], with the P3 component peaking 1 ms earlier in congruent (351 ms) compared to incongruent trials (352 ms). The main effect of componential numerical distance was not significant, $\chi^2(1) = 2.40$, $p = .122$, $b = 0.27$, 95% CI [-0.07, 0.61], while the main effect of log-transformed global numerical distance was significant, $\chi^2(1) = 9.91$, $p = .002$, $b = 0.58$, 95% CI [0.22, 0.94]. Finally, the Number-Length-Component Congruity × Number Length Distance interaction was not significant, $\chi^2(1) = 3.03$, $p = .082$, $b = -0.99$, 95% CI [-2.11, 0.13].

Discussion

The results of Experiment 1 demonstrated clear effects of automatic processing in multi-digit number comparisons, with both behavioral and ERP evidence supporting our hypotheses about the interplay between number length and digit identity. The behavioral data revealed a number-length-component congruity effect, with faster responses to congruent compared to incongruent trials, confirming our prediction that task-irrelevant number length would influence performance even when participants were instructed to focus solely on digit identity. This finding aligns with previous research demonstrating automatic processing of numerical information (e.g., [18,21,78−85]). Importantly, we observed a significant interaction between number-length-component congruity and number length distance, with the congruity effect emerging only for trials with number length distance of 2, but not for

trials with a number length distance of 1. This pattern partially supports our hypothesis that

increased number length distance would enhance interference from the task-irrelevant

dimension. However, the complete absence of a number-length-component congruity effect at

number length distance 1 was unexpected, and may be partially understood within the

framework of Schwarz and Ischebeck's coalescence model [48].

The coalescence model [48] proposes that information from both relevant and

irrelevant dimensions is automatically processed and combined into an overall decision

signal, with the degree of interference depending on the salience of the irrelevant dimension.

Crucially, highly discriminable irrelevant attributes (those further from the standard) generate

stronger signals that are harder to ignore. The model thus predicts that number length

distance 2 (e.g., 1-digit or 5-digit numbers compared to the 3-digit standard) should produce

stronger interference than distance 1 (e.g., 2-digit or 4-digit numbers), consistent with our

finding of a robust number-length-component congruity effect only at number length distance

2. However, the model anticipated gradual modulation rather than the complete absence of

effects at number length distance 1. This complete absence of the effect at the smaller

distance suggests that, at number length distance 1, digit identity information may have

reached the decision threshold before number length information accumulated sufficiently to

influence the response.

Building on the behavioral results, the ERP findings provided further insights into the

neural mechanisms underlying multi-digit number processing. The N1 component (120–150

ms) showed sensitivity to number length distance, with greater negativity for distance 2

compared to distance 1. This finding was obtained using stimuli carefully designed to

equalize overall visual size through scribbled line patterns, thereby isolating effects related to

number length rather than general visual properties. Therefore, this early N1 sensitivity

suggests that the brain extracts number length information during initial perceptual encoding,

supporting the hypothesis that a crude process for estimating numerical magnitude operates at this very early processing stage (e.g., [21,23,28−31]). This represents the first electrophysiological evidence that the syntactic structure of numbers, in which longer numbers typically represent larger values, can influence processing as early as the initial encoding stage. In line with this, the P2p component (150–190 ms) also reflected sensitivity to number length distance, with greater positivity for distance 1 compared to distance 2. This component has been associated with numerical distance processing in previous studies (e.g., [52,60,62−66]), and our finding of a significant effect of componential numerical distance on P2p amplitude supports this association. Taken together, the sequential effects in N1 and P2p suggest a progression from early syntactic encoding to more refined numerical processing.

Extending this sequence, the P3 component (300–360 ms) revealed neurophysiological evidence of conflict processing, with significantly reduced amplitude for number-length-component incongruent compared to congruent trials. In addition, the difference in latency between congruent and incongruent trials was significant though extremely small (1 ms). This aligns with previous findings suggesting that the P3 component reflects conflict in numerical processing tasks (e.g., [50−55]).

Overall, the present findings support our recently proposed theoretical framework ([21], see also [23]), which postulates that number comparisons involve parallel processes: a crude process that evaluates the binary question of "which is smaller/larger?", and a refined process that determines "by how much smaller/larger?". Our ERP data provide new temporal insights into these processes, with number length information extracted during early perceptual encoding (N1), followed by more refined numerical analysis (P2p), and culminating in conflict resolution (P3). The behavioral interaction between number-length-component congruity and number length distance further suggests that these processes may be differentially engaged depending on the physical properties of the stimuli.

Taken together, these findings extend our understanding of the syntactic contributors to multi-digit number processing by demonstrating that the physical length of numbers automatically influences numerical judgments even when it is explicitly task irrelevant. This aligns with the notion that number length serves as a primary indicator for estimating numerical magnitude (e.g., [16−23]). The results also suggest that while conflict between number length and digit identity is resolved at a relatively late stage of processing (P3), the initial encoding of number length information occurs during early perceptual analysis (N1). This pattern provides new insights into the sequential unfolding of the component processes involved in multi-digit number comparison.

Experiment 2: Physical Comparison Task

Experiment 2 was identical to Experiment 1 in all aspects except the task instructions. In Experiment 2, participants were instructed to perform a physical comparison task, deciding if the length of the displayed target number was smaller or larger than the length of the standard number "555", while ignoring digit identities. We expected participants to show interference from the task-irrelevant digit identity dimension while focusing on the physical number length dimension, though this number-length-component congruity effect would be attenuated compared to Experiment 1 due to the higher salience of number length (e.g., [18,21,78−85]).

Consistent with previous research (e.g., [23,34,38,40,41,43,47−49,70]), we hypothesized that number length distance would modulate the number-length-component congruity effect, with a smaller congruity effect and faster responses when number length distance was 2 compared to 1. At the neurophysiological level, our expectations for ERP components mirrored those of Experiment 1.

Method

Participants

23

1   Twenty-seven undergraduate psychology students (aged 20-27 years, average age

2   22.41 years, 22 female, 5 male, 2 left-handed, 23 native Hebrew speakers, 3 native English

3   speakers, and 1 native French speaker) from Ariel University participated in the experiment

4   in exchange for course credit.

5   *Procedure*

6   Participants were instructed to decide if the number length of the displayed target

7   number was smaller or larger than the number length of the standard "555", while ignoring

8   digit identities. They pressed the "A"/"L" key on the keyboard if they chose "shorter"/

9   "longer", respectively.

10   *EEG recording and analysis*

11   On average, 1,113.30 (SD = 51.86) epochs were retained for each participant for the

12   analyses. Table 2 presents an overview of the mean number of retained trials per participant

13   and condition of interest.

14

15   *Table 2.* Experiment 2 – Mean retained number of epochs per participant and condition.

Factor	Level	Mean	SD
Number length distance	1	549.48	28.76
Number length distance	2	563.81	24.80
Componential numerical distance	1	369.81	18.02
Componential numerical distance	2	371.96	19.02
Componential numerical distance	3	371.52	17.2
Number-length-component congruity	Congruent	557.11	28.04
Number-length-component congruity	Incongruent	556.19	25.68

16

17   All other details of the methodology were identical to those described in Experiment

18   1.

19   **Results**

20   *Behavioral analysis*

The main effect of number length distance was significant, $\chi^2(1) = 90.97$, $p < .001$, $b = 16.24$, 95% CI [12.90, 19.58], reflecting faster responses to trials with number length distance of 2 (463 ms) compared to a distance of 1 (479 ms). In contrast to the findings from Experiment 1, the main effect of number-length-component congruity was not significant, $\chi^2(1) = 1.11$, $p = .292$, $b = 1.71$, 95% CI [-1.47, 4.89]. In addition, the main effect of componential numerical distance did not reach significance, $\chi^2(1) = 1.54$, $p = .214$, $b = -1.22$, 95% CI [-3.15, 0.71], while the main effect of log-transformed global numerical distance was significant, $\chi^2(1) = 234.49$, $p < .001$, $b = -15.83$, 95% CI [-17.85, -13.80]. Finally, the Number-Length-Component Congruity × Number Length Distance interaction was not significant, $\chi^2(1) = 0.86$, $p = .354$, $b = 2.98$, 95% CI [-3.32, 9.29].

ERP analysis

    N1 component (120−150 ms; electrodes: Oz, O1, POz, PO3). As in Experiment 1, a significant main effect of number length distance was found, $\chi^2(1) = 70.34$, $p < .001$, $b = 0.83$, 95% CI [0.64, 1.02] (Figure 6), reflecting greater negativity for distance 2 (–0.95 μV) compared to distance 1 (–0.12 μV). In contrast, the main effect of number-length-component congruity was not significant, $\chi^2(1) = 1.98$, $p = .159$, $b = -0.13$, 95% CI [-0.32, 0.05]. Moreover, both main effects of componential numerical distance, $\chi^2(1) = 10.30$, $p = .001$, $b = -0.18$, 95% CI [-0.30, -0.07], and log-transformed global numerical distance, $\chi^2(1) = 104.23$, $p < .001$, $b = 0.61$, 95% CI [0.50, 0.73], were significant. Lastly, the Number-Length-Component Congruity × Number Length Distance interaction was not significant, $\chi^2(1) = 0.90$, $p = .344$, $b = 0.18$, 95% CI [-0.19, 0.54].

Figure 6. Experiment 2 – ERP traces and topographic distribution for the N1 component.
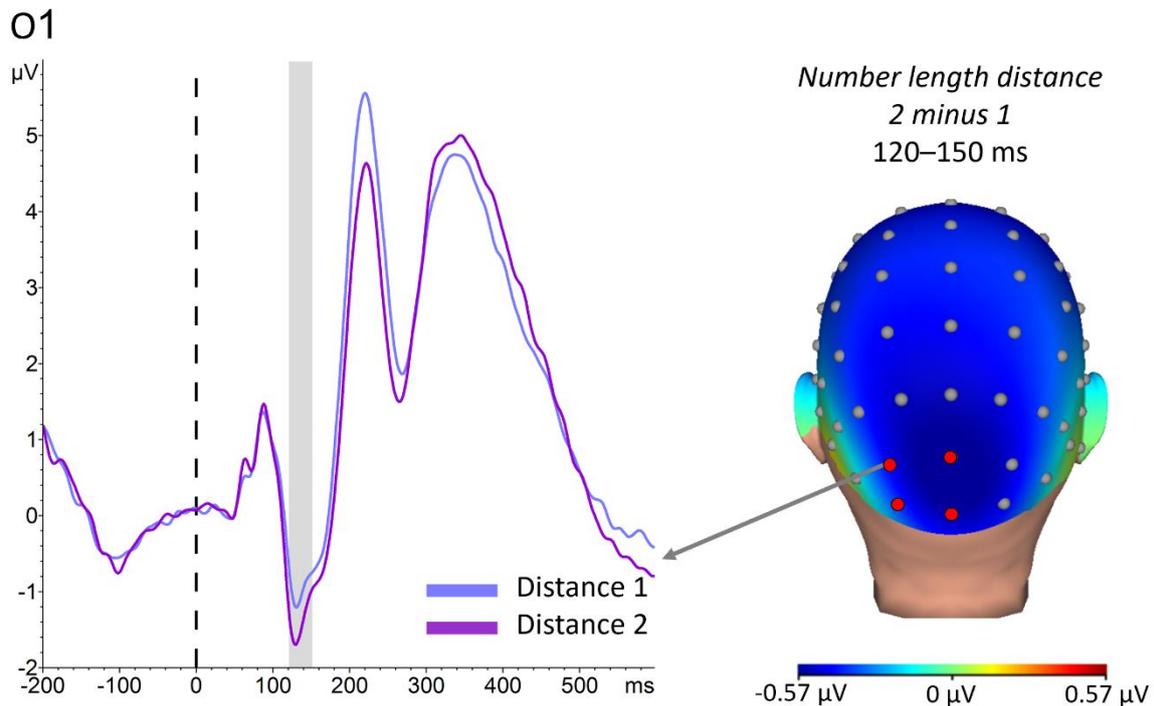
P2p component (150−190 ms; electrodes: FC1, FCz, FC2, C1, Cz, C2, CP1, CPz, CP2). A significant main effect of number length distance, $\chi^2(1) = 32.94$, $p < .001$, $b = 0.68$, 95% CI [0.45, 0.91], reflected greater positivity for distance 1 (2.75 μV) compared to distance 2 (2.07 μV). The main effect of number-length-component congruity was not significant, $\chi^2(1) = 3.70$, $p = .055$, $b = 0.22$, 95% CI [0.00, 0.44]. In addition, both main effects of componential numerical distance, $\chi^2(1) = 47.90$, $p < .001$, $b = -0.47$, 95% CI [-0.61, -0.34] (Figure 7), and log-transformed global numerical distance, $\chi^2(1) = 120.11$, $p < .001$, $b = 0.78$, 95% CI [0.64, 0.92], were significant. Finally, the Number-Length-Component Congruity × Number Length Distance interaction was not significant, $\chi^2(1) = 0.19$, $p = .660$, $b = -0.10$, 95% CI [-0.53, 0.34].

Figure 7. Experiment 2 – ERP traces and topographic distribution for the P2p component.
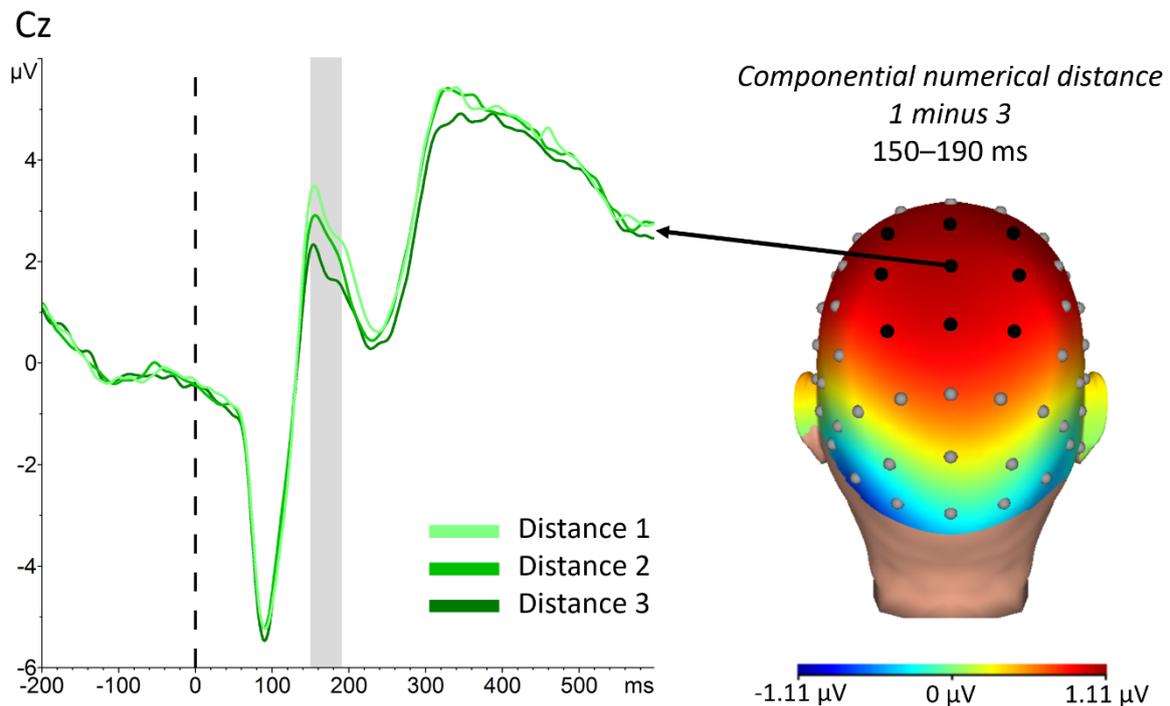
P3 component (300−360 ms; electrodes: C1, Cz, C2, CP1, CPz, CP2, P1, Pz, P2). P3 amplitude analysis revealed a significant main effect of number length distance, $\chi^2(1) = 20.09$, $p < .001$, $b = 0.55$, 95% CI [0.31, 0.80], reflecting greater positivity for distance 1 (6.18 µV) compared to distance 2 (5.62 µV). The main effect of number-length-component congruity was significant, $\chi^2(1) = 4.66$, $p = .031$, $b = 0.25$, 95% CI [0.02, 0.49], reflecting a reversed number-length-component congruity effect with greater centro-parietal positivity for incongruent (6.03 µV) compared to congruent (5.77 µV) trials (Figure 8). Moreover, both main effects of componential numerical distance, $\chi^2(1) = 10.56$, $p = .001$, $b = -0.23$, 95% CI [-0.37, -0.09], and log-transformed global numerical distance, $\chi^2(1) = 175.73$, $p < .001$, $b = 1.00$, 95% CI [0.85, 1.14], were significant. Finally, the Number-Length-Component Congruity × Number Length Distance interaction was not significant, $\chi^2(1) = 0.09$, $p = .769$, $b = 0.07$, 95% CI [-0.39, 0.53]. As a robustness check paralleling Experiment 1's P3 amplitude analysis, we fitted a GLMM that excluded log-transformed global numerical distance. In this

27

1   reduced model, the number-length-component congruity effect was not significant, $\chi^2(1) =$

2   0.14, $p = .713$, $b = 0.04$, 95% CI [-0.19, 0.27]. Diagnostic analyses ruled out multicollinearity

3   and loss of power, and confirmed that the model including log-transformed global numerical

4   distance provided superior fit to the data. The results indicated that the reduction in the

5   congruity effect when log-transformed global numerical distance is included is attributable to

6   shared variance rather than multicollinearity. The full analysis is detailed in the

7   Supplementary Materials (Experiment 2).

8

9   *Figure 8.* Experiment 2 – ERP traces and topographic distribution for the P3 component.
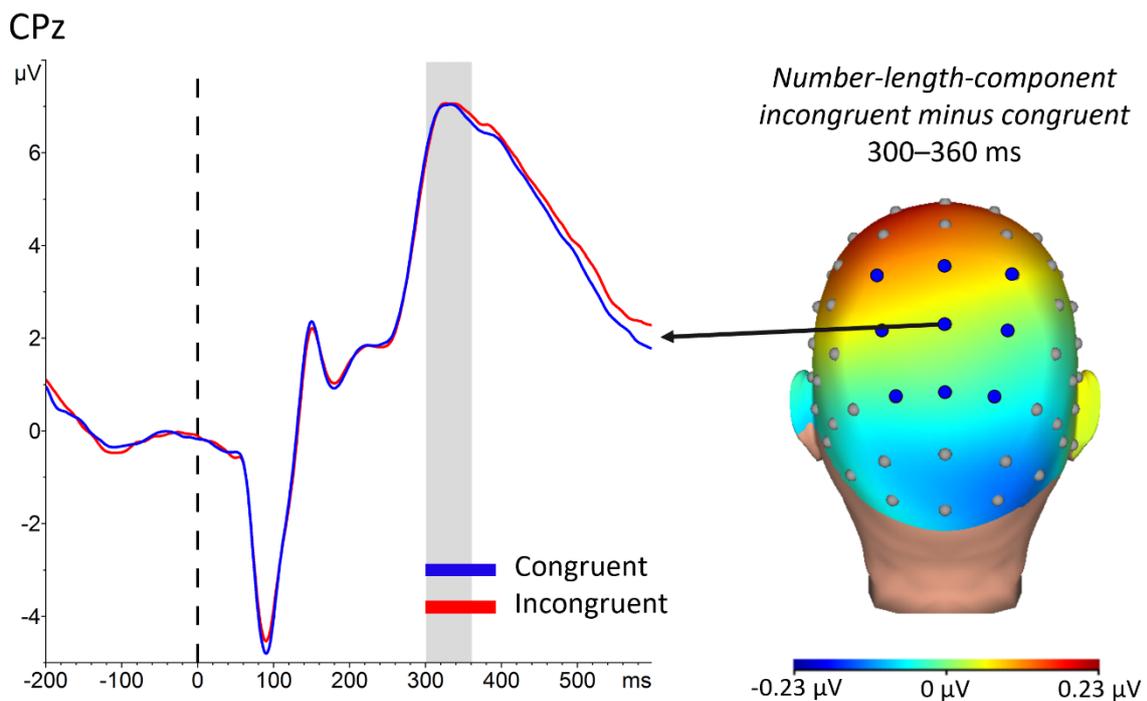
10

11

12   The P3 latency analysis did not reveal any significant effects for number length

13   distance, $\chi^2(1) = 0.68$, $p = .408$, $b = -0.25$, 95% CI [-0.83, 0.34]; number-length-component

14   congruity, $\chi^2(1) = 0.17$, $p = .684$, $b = 0.12$, 95% CI [-0.44, 0.67]; componential numerical

15   distance, $\chi^2(1) = 2.10$, $p = .148$, $b = -0.25$, 95% CI [-0.59, 0.09]; log-transformed global

16   numerical distance, $\chi^2(1) = 3.14$, $p = .076$, $b = -0.32$, 95% CI [-0.68, 0.03]; and the Number-

Length-Component Congruity × Number Length Distance interaction, $\chi^2(1) = 0.01$, $p = .908$,

$b = -0.07$, 95% CI [-1.17, 1.04].

Discussion

In Experiment 2, participants were instructed to focus solely on number length while ignoring digit identities, creating a complementary task to Experiment 1. Unlike Experiment 1, the behavioral data revealed no significant number-length-component congruity effect, and no interaction between number-length-component congruity and number length distance, indicating that participants could effectively focus on the physical dimension without interference from task-irrelevant digit identity.

At the neurophysiological level, the N1 component (120–150 ms) showed strong sensitivity to number length distance, with greater negativity for distance 2 compared to distance 1. This early encoding of physical length, independent of confounding visual properties due to our controlled stimuli design, provides compelling evidence that number length information is processed during initial perceptual stages. Notably, componential numerical distance (digit value) significantly modulated this early component, suggesting that semantic properties of individual digits are also processed during this initial stage, even though they do not yet significantly interfere with the physical dimension. This finding aligns with the notion of parallel processing streams where both syntactic structure (number length) and semantic content (digit value) are extracted early, though processed with differential priority.

Interestingly, this significant effect of componential numerical distance on the N1 was observed in Experiment 2, where participants focused on physical length, but not in Experiment 1, where digit value was the task-relevant dimension. This asymmetrical pattern suggests that processing of numerical dimensions may be modulated by task demands. When participants were explicitly instructed to attend to digit identity (Experiment 1), processing

may have followed a more controlled pathway, whereas when digit value was task-irrelevant (Experiment 2), it appears to have been processed via automatic pathways that influenced early perceptual encoding. This aligns with Naparstek and Henik's [80,81] findings regarding the task-dependent nature of automatic numerical processing, where they demonstrated that automatic activation of numerical information can vary based on task requirements. The presence of digit value effects in the N1 component specifically when this dimension was task-irrelevant provides electrophysiological evidence for parallel processing of multiple numerical dimensions at early perceptual stages, with attention allocation affecting the timing and pathway of these processes.

Similar to the pattern in Experiment 1, the subsequent P2p component (150–190 ms) showed sensitivity to both number length distance and componential numerical distance, but showed no significant number-length-component congruity effects. This suggests that while both stimulus dimensions are being processed at this stage, they may be operating through separate pathways with limited integration. The significant effect of componential numerical distance on P2p amplitude further supports the notion that numerical magnitude information is being extracted during this time window, consistent with previous research (e.g., [52,60,62−66]).

By the P3 time window (300–360 ms), the number-length-component congruity effect was reversed compared to Experiment 1 when log-transformed global numerical distance was included as a covariate, with number-length-component incongruent trials showing enhanced rather than reduced P3 amplitude. As detailed in the Supplementary Materials, this reversal reflects shared variance: log-transformed global numerical distance is jointly determined by both digit identity and number length, so number-length-component congruent and incongruent trials cluster systematically along this dimension. When log-transformed global numerical distance is included as a covariate, it accounts for the overlap with the number-

length-component congruity effect, revealing congruity's unique contribution after controlling for overall magnitude differences. This pattern was consistent across both experiments. This reversed pattern is also compatible with previous research showing inverted size congruity effects when processing involves perceptual rather than numerical mechanisms [89].

The overall pattern of P3 amplitude results can be explained by two complementary accounts. According to a saliency-based account aligned with Schwarz and Ischebeck's coalescence model [48], the interference patterns observed in the numerical Stroop effect depend on the relative discriminability of competing dimensions, with the more discriminable dimension interfering more with the less discriminable one (e.g., [82,88]). In our study, number length differences (e.g., between a 5-digit number and the 3-digit standard) are likely more perceptually salient than digit identity differences. When dimensions are processed in parallel, the more salient dimension is processed faster and "wins the race", with responses executed before the slower dimension can exert influence. This prevents conflict from emerging at later processing stages, as evidenced by the absence of P3 congruity effects in Experiment 2. The model predicts interference should only emerge when processing speeds are sufficiently close, explaining why P3 congruity effects appeared in Experiment 1 (digit identity task-relevant) but not Experiment 2 (number length task-relevant).

Alternatively, a cognitive control account proposes that participants actively suppress task-irrelevant digit identity through inhibitory control when number length is task-relevant. Strategic allocation of attention enhances relevant dimension processing while inhibiting the irrelevant dimension, preventing interference. Supporting this view, our central-parietal P3 distribution aligns with electrode sites where late positive components have been linked to conflict monitoring and cognitive control in numerical Stroop tasks (e.g., [90,91]), to response inhibition in Go/NoGo paradigms (e.g., [92,93]), and with the classic centro-parietal P3b topography associated with context updating and attentional allocation [94]. The

presence of P3 congruity effects in Experiment 1 suggests that inhibiting the more salient

number length dimension is more difficult, requiring conflict resolution at later stages. These

accounts need not be mutually exclusive: saliency may establish baseline processing speed

differences, while task instructions and cognitive control modulate how these differences

influence behavior.

General Discussion

The present study investigated the electrophysiological correlates of multi-digit

number processing, focusing on the interplay between number length and numerical value

under conditions of intentional and automatic processing. Through two complementary

experiments (one emphasizing digit identity and the other number length), we gained novel

insights into how these dimensions interact at different processing stages. Our study's

contribution lies in controlling for overall visual size while isolating number length effects,

using a comparison-to-standard paradigm, and employing tie numbers to eliminate within-

number compatibility effects. These methodological approaches allowed us to capture more

nuanced aspects of multi-digit number processing not observed in previous research.

Most importantly, we found clear evidence of early encoding of number length in the

N1 component (120–150 ms post-stimulus onset). By equalizing overall visual sizes through

scribbled line patterns, we isolated effects specifically related to number length rather than

general stimulus size. This early sensitivity was observed across both experiments, with

enhanced parieto-occipital N1 negativity for longer numbers, suggesting that the brain

differentiates number length during early perceptual processing stages. Importantly, in

Experiment 2 (physical comparison), but not Experiment 1 (numerical comparison), the N1

component also showed sensitivity to componential numerical distance (digit value),

indicating that task instructions modulate which dimensions are prioritized during early

processing (e.g., [80,81]). These findings provide the first electrophysiological evidence that

number length information is processed independently of general visual properties during early visual perception, supporting the hypothesis that a crude process for numerical magnitude estimation operates at this early processing stage [21,23].

Our results reveal three distinct temporal stages in multi-digit number processing: early parallel encoding of number length and digit value (N1, 120–150 ms post-stimulus onset), refined numerical distance processing (P2p, 150–190 ms post-stimulus onset), and later cognitive conflict resolution (P3, 300–360 ms post-stimulus onset). This temporal sequence suggests the brain extracts information about both physical and semantic properties in parallel before integrating them at later stages, extending models of multi-digit number processing by adding a crucial temporal dimension (e.g., [3,8,12−14,21,30]). The central P2p component showed consistent sensitivity to numerical distance measures in both experiments, with greater positivity for shorter than longer number length distances. Additionally, it demonstrated significant modulation by componential numerical distance and (log-transformed) global distance, aligning with previous research identifying this component as an index of numerical magnitude processing (e.g., [52,60,62−66]). Although some of the behavioral effects were small in absolute terms (e.g., RT differences of only a few milliseconds) they were consistent across participants and statistically reliable. These small behavioral differences align with the early ERP results, where number length distance and (componential and global) numerical distance are already separated at the N1 and P2p stages. Taken together, the behavioral and ERP findings suggest that number length is encoded early and treated as a salient dimension in multi-digit number processing, even when it is not the main focus of the task.

The centro-parietal P3 results suggest that (log-transformed) global numerical distance was closely related to conflict processing mechanisms across both experiments. When global distance was not accounted for as a covariate, we observed expected effects: in

Experiment 1 (numerical comparison), number-length-component incongruent trials showed

reduced P3 amplitude and delayed latency compared to congruent trials, consistent with

increased processing demands when resolving conflicts between dimensions. In Experiment 2

(physical comparison), no significant number-length-component congruity effect emerged

under the same analytical conditions. Hence, congruity effects appeared only when numerical

magnitude was task-relevant, aligning with our behavioral findings where Experiment 1

showed significant number-length-component congruity effects while Experiment 2

demonstrated participants' ability to effectively focus on the physical dimension.

The task-dependent modulation of number-length-component congruity effects

highlights the importance of attention allocation in numerical cognition models. Attentional

focus modulated the direction and magnitude of conflicts between dimensions at the P3 stage

(300–360 ms post-stimulus), with opposite patterns depending on task relevance. No

significant number-length-component congruity effects emerged at the earliest N1 or P2p

stages in either experiment, indicating that while both physical and semantic properties are

processed in parallel early on, their integration and conflict resolution occur only at later

processing stages.

Our findings are most compatible with hybrid models (e.g., [11,13,14]) that allow for

parallel activation of multiple representational levels. Specifically, the temporal sequence we

observed (early number length encoding in N1, followed by refined magnitude processing

incorporating both componential and global distance in P2p, and finally conflict resolution in

P3) suggests that both holistic (global magnitude, number length) and decomposed

(individual digit values) representations are activated in parallel and subsequently integrated.

This pattern is difficult to reconcile with purely holistic or purely decomposed accounts.

Beyond multi-digit number processing specifically, our findings have broader

implications for understanding how the visual properties of numerical symbols influence

cognition. The early processing of number length provides empirical support for the notion that the syntactic structure of numbers (where longer numbers typically represent larger values in the Hindu-Arabic number system) influences processing from the initial encoding stage, adding a crucial temporal dimension to models of multi-digit number processing (e.g., [3,8,12−14,21,30]). This suggests that our cognitive system is highly tuned to the visual-spatial properties of numerical notation, likely through extensive experience with this culturally invented symbolic system (e.g., [1]).

Study Limitations and Future Directions

Despite the contribution of our findings, several limitations of the current study warrant consideration and suggest directions for future research. First, we focused on tie numbers to control for potential influences of within-number compatibility effects. While this approach allowed us to isolate the effects of number length and digit identity, future research should extend these findings to more ecologically valid multi-digit numbers composed of different digits. This would enable examination of how within-number compatibility (e.g., unit-decade compatibility, [14]) interacts with number length effects at different processing stages.

Second, our study examined only specific number length distances (1 and 2). Future research could benefit from a parametric manipulation of number length differences (e.g., [22]) to establish whether the relationship between physical length distance and congruity effects follows a linear or non-linear pattern. This would provide further insights into the relative salience of physical length cues at different magnitudes of difference. Third, while our analyses focused on amplitude changes in specific time windows, future studies could employ continuous EEG measures or source localization techniques to better trace the flow of information between brain regions involved in processing physical and semantic aspects of multi-digit numbers. Such analyses might reveal additional neural mechanisms, particularly

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those related to functional connectivity between brain regions involved in numerical

cognition. Fourth, developmental studies could investigate how the sequential stages of

multi-digit number processing change with age and education. Given that understanding

multi-digit numbers involves both innate numerical abilities and culturally acquired

knowledge about place-value notation, examining how these processes emerge

developmentally could provide valuable insights into the interplay between biological and

cultural factors in numerical cognition.

Fifth, our interpretation of the saliency advantage of number length raises questions

about the generalizability of our findings across different saliency conditions. The numerical

Stroop literature demonstrates that interference patterns depend on the relative

discriminability of competing dimensions (eg., [39,82,88]). Future research could

systematically manipulate the relative saliency of number length versus digit identity (e.g.,

using highly similar number lengths with highly distinct digit values, varying the number of

stimulus levels, or employing stimulus degradation) to determine whether our findings reflect

dimension-general mechanisms or depend on the specific saliency hierarchy present in

standard multi-digit number notation. Such manipulations would help clarify whether the

dissociation we observed between early parallel processing (N1, P2p) and late selective

control (P3) generalizes across saliency conditions or requires the task-relevant dimension to

have a saliency advantage for successful selective suppression.

Beyond these limitations, we note an interesting pattern in our data that warrants

further investigation. The N1 component showed a left-lateralized distribution across both

experiments. The functional significance of this lateralization at such an early processing

stage (~120-150 ms) remains unclear. Previous research has documented hemispheric

specialization in numerical processing, with the left hemisphere particularly involved in

symbolic magnitude processing (e.g., [94−96]) and the right hemisphere in processing

continuous quantities (e.g., [97−98]). However, these patterns of functional specialization typically emerge at later ERP components. Whether similar functional specialization exists at this early N1 stage, or whether this lateralization reflects other aspects of visual processing of symbolic stimuli, is unclear. Source localization methods in future studies would be valuable for identifying the neural generators underlying this early lateralized response and clarifying its functional significance for number processing.

An important consideration is the extent to which our observed effects reflect specifically syntactic processing of multi-digit number structure versus more general perceptual enumeration processes. While our stimuli consisted of integrated numerical strings requiring syntactic parsing (e.g., determining that "2222" represents two thousand two hundred twenty-two rather than four separate twos), we cannot definitively rule out contributions from perceptual object enumeration mechanisms. However, several aspects of our findings support a role for syntactic processing beyond general enumeration: (1) the N1 modulation follows absolute distance from the three-digit standard rather than simple object count, with 1- and 5-digit numbers showing similar patterns despite differing in numerosity, (2) number length distance in our paradigm is tightly coupled to order-of-magnitude differences in representable values, suggesting processing beyond simple enumeration, and (3) the early time course of number length encoding aligns with syntactic parsing mechanisms identified in previous research (e.g., [28,30,31,99]). Future research using paradigms that directly contrast multi-digit numbers with enumeration displays (e.g., [79,80,83]), as well as including comparison to non-numerical stimuli, could further clarify the unique contributions of syntactic processing.

A final important methodological consideration concerns statistical power for detecting interaction effects. Our sample size (N = 27 per experiment) was optimized for detecting main effects, which were our primary hypotheses. While this sample size is comparable to published studies in this domain, interaction effects typically require substantially larger samples than main effects. Consequently, non-significant interactions should generally be interpreted cautiously as inconclusive rather than as evidence for null

effects. Specifically, the exploratory non-significant Number-Length-Component Congruity ×

Number Length Distance interaction in Experiment 2 should be interpreted cautiously.

Alternative explanations include: (1) genuine absence of interaction when number length is

task-relevant, (2) insufficient power to detect a smaller interaction, or (3) task-dependent

modulation from different instructions ("numerically larger" vs. "longer number").

Importantly, this limitation does not affect our primary conclusions regarding the N1

component, which are based on well-powered main effect tests. Future research specifically

designed to investigate interaction patterns in ERP measures would require larger samples

and a priori hypotheses focused on such effects.

Conclusion

In conclusion, our study provides novel electrophysiological evidence for three

temporally distinct stages of multi-digit number processing. We demonstrated early encoding

of number length in the N1 component (~120–150 ms) independent of overall visual size,

refined magnitude comparison in the P2p component (~150–190 ms), and conflict resolution

in the P3 component (~300–360 ms) only when numerical magnitude was task-relevant.

Crucially, number length acts as a primary syntactic cue to magnitude from the initial

encoding stage onward, providing neurophysiological evidence for models highlighting the

foundational role of numerical syntax in magnitude evaluation. These findings underscore

how numerical notation systems shape cognitive processing, with implications for

educational practices and interventions for mathematical difficulties.

Data Availability

Materials and data are available via the Open Science Framework at

https://osf.io/5zrw9/files

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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