Neurobehavioral Dynamics of Numerical Change: Directional and Numerical Distance Processing

Vanessa Rhee, Zhiyi Chen, Mischa Gushiken, Kiren Bakhru, Hanyi Xu, Nick Bisbee, Yuexin Li, Jean Ee Tang, Peter Gordon.
Teachers College, Columbia University; Johns Hopkins University; New York University

Introduction

Dual Systems of Number
Research suggests two systems for processing quantity: Parallel Individuation (PI) for small numbers (1–3) and the Approximate Number System (ANS) for large numbers (4+).

Hyde & Spelke and the Present Study
Previous EEG studies (e.g., Hyde & Spelke, 2012) show that the early posterior **N1** component scales with small numerosities, whereas larger numbers are processed later according to numerical ratio, suggesting distinct neural mechanisms for exact and approximate number processing. Hyde & Spelke used **small numbers (1–3) and larger sets (8, 16, 24)** under **passive** viewing. The present study **builds on and extends Hyde & Spelke's findings** by examining neural responses to numerical change using an active oddball paradigm, while differentiating the **direction** and **numerical distance** of change. Instead of contrasting small and very large sets, we used small numbers (1–3) and larger sets (4–6), which is a **continuum beyond small numbers**. We also collected **behavioral responses** (reaction time and accuracy) and analyzed **P1–N1 peak-to-peak responses**, and **mismatch negativity (MMN)** in addition to **N1 latency and amplitude**.

Methods

Paradigm: Active Change Detection

Participants, Stimuli & Trial Structure

Participants & Stimuli: N=24 right-handed adults viewed sequential arrays of 1–6 dots (controlled for cumulative area/luminance).

Timing: 250 ms stimulus duration; 750–1250 ms jittered ISI.

Habituation: 3–5 repeats of a "prime" number (e.g., four consecutive '3's) to establish a baseline.

Task: Participants actively monitored the stream and pressed a key upon detecting any numerical change.

Target: A final stimulus appeared as one of three conditions:

- **No Change:** Same numerosity (e.g., 3→3).
- **Within-Range Change:** Change within Small (1–3) or Large (4–6) sets.
- **Crossover Change:** Change crossing the small/large boundary (e.g., 3→4).

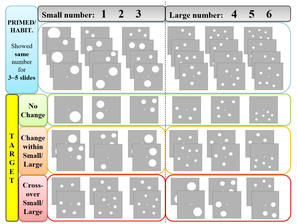

Fig. 1 Current Study Design & Examples of Numerical Stimuli

EEG Acquisition and Pre-processing

Recording & Preprocessing: 128-channel EGI Geodesic Sensor Net. Data were bandpass filtered (0.1–35 Hz online), low-pass filtered (40 Hz), 250 Hz sampling, and re-referenced to the average.

Epochs: Segmented **-100 ms to 600 ms** relative to stimulus onset.

ERP Component Analysis

Regions of Interest (ROIs): Analyses were conducted over two a priori spatial ROIs (see Fig. 2):

- **Bilateral POT (P1/N1)**: Parietal-Occipital-Temporal junction (Left: 66, 65, 59, 60, 67, 71, 70; Right: 84, 76, 77, 85, 91, 90, 83).
- **Midline Frontal (MMN)**: Fz electrodes to index automatic change detection (4, 5, 10, 11, 12, 16, 18, 19).

ERP components were extracted using MNE-Python (Gramfort et al., 2013). Peaks were identified using a collapsed localizer, and mean amplitude and 50% fractional area latency were computed for P1 (80–120 ms), MMN (100–120 ms), and N1 (125–200 ms).

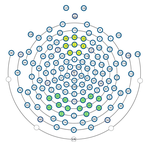

Fig. 2 Map of electrode groupings used for averaging and analysis: Fz area (yellow) and POT (green)

Behavioral Results: Distance & Direction

Reaction times decreased with **greater numerical distance** between primed and target, e.g., a numerical distance of 3 was detected faster than a numerical distance of 1 ($p < .001$).

Accuracy was significantly higher for decreasing changes compared to Increasing changes ($p < 0.01$).

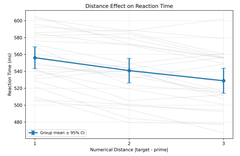

Fig. 3 Distance Effect on Reaction Time

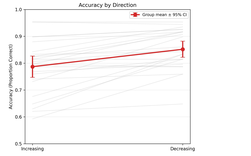

Fig. 4 Accuracy by Direction (Increasing or Decreasing)

The RT distance effect suggests that participants processed numerical magnitude during the task. We next examined whether this effect was reflected in **early neural responses**.

N1 Scaling & Numerical Distance

Numerical Scaling
Hyde & Spelke (2009, 2012) showed that during passive viewing, early neural responses (N1) at posterior sites scale with cardinal value for small numbers. Do these signatures persist during active numerical change detection?
Following Hyde & Spelke (2009), we collapsed across primed contexts to examine N1 mean amplitude as a function of target numerosity (1, 2, or 3). **N1** amplitude over bilateral POT became **more negative with increasing cardinal value,** as in the previous studies. The linear contrast was significant ($p<.001$).

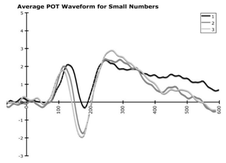

Fig. 5 Numerical scaling for small numbers (Hyde & Spelke, 2009).

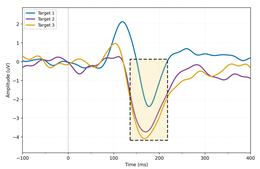

Fig. 6 Numerical scaling for small numbers.

Magnitude vs Latency
Hyde & Spelke (2009) found that large numerosities elicited a faster and larger N1 than small numerosities. They argued that this latency difference reflects attentional selection, as large sets are processed as a single group, whereas small sets require selecting multiple individual items in parallel. In our data**, N1 mean amplitude showed a more negative trend** for large than small targets ($p = .0896$), consistent with Hyde & Spelke (2012). However, N1 mean latency did not show a significant small–large difference.

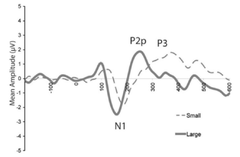

Fig. 7 Small vs Large N1 (Hyde & Spelke, 2012)

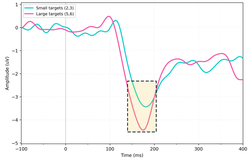

Fig. 8 Small vs Large N1

N1 (Increasing vs Decreasing)
Increasing transitions (green) elicited a **more negative and earlier** N1 than decreasing transitions (red), based on N1 mean amplitude and 50% fractional-area latency. These results suggest that the **brain may allocate attention to increasing numerical changes earlier** than to decreasing changes.

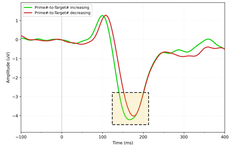

Fig. 9 Increasing vs Decreasing N1

These results show a trend that **latency interacts with direction of change** (increasing or decreasing), while **amplitude interacts with the size of target** (small or large) and **direction.**

Future Directions

P1–N1 peak-to-peak

To test whether the behavioral distance effect is reflected in early visual processing, we measured **P1–N1 peak-to-peak** mean amplitude over bilateral POT, collapsed across direction. **Amplitude scaled with numerical distance**, suggesting that **early perceptual responses encode the magnitude of numerical change.**

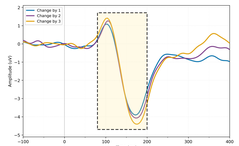

Fig. 10 P1–N1 peak-to-peak waveforms over bilateral POT by numerical distance. Δ values reflect mean amplitude difference between P1 and N1 windows.

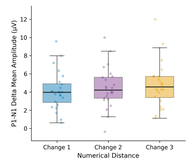

Fig. 11 P1–N1 delta mean amplitude by numerical distance (N = 24). Individual dots represent participants.

Frontal Mismatch Negativity (MMN)

Active Change Detection
Unlike passive paradigms, our active monitoring task elicited **MMN** at Fz, which indexes the automatic detection of numerical error. **Increasing** changes **peaked earlier** than Decreasing changes indicating faster frontal mismatch detection for additions than subtractions.

Distance Effect
For **decreasing** conditions, **MMN** mean amplitude showed **graded scaling with numerical distance.** The MMN was shallowest for a decrease of 1 (−0.34 μV), intermediate for 2 (−0.71 μV), and most negative for 3 (−1.05 μV), mirroring behavioral performance: **the larger the numerical decrease, the stronger the mismatch response** and **the higher the accuracy**.

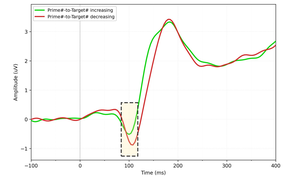

Fig. 12 Frontal (Fz) ERP waveforms for Increasing (green) and Decreasing (red) numerosity changes, collapsed across all distances.

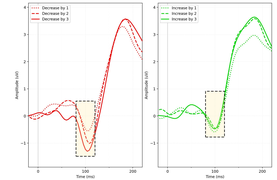

Fig. 13 Frontal (Fz) ERP waveforms for Decreasing (red) and Increasing (green) numerosity changes by numerical distance

Conclusions

Active Change Detection: In this active task, we observed a frontal MMN not previously reported in passive numerosity studies, alongside the posterior N1 signatures described by Hyde & Spelke (2009, 2012).

Direction Matters: The brain processes "addition" (Increasing) and "subtraction" (Decreasing) of quantity differently. Decreasing changes elicit higher accuracy and stronger frontal error signals (MMN).

Distance Effect: Neural error signals scale with the magnitude of the numerical change, mirroring behavioral performance.

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