ERP Markers of Semantic Activation During Enumeration are Linked to Counting Ability

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Background

- The purpose of this study was to identify and better understand the neural characteristics of adults' enumeration skills. Enumeration refers to the ability to determine the number of objects in a set.[1] This fundamental number skill is a building block for math development, and is linked to math achievement.[2]
- This study had two components:
  - A **visual enumeration task** (adapted from Pagano, Lombardi, and Mazza, 2014[3]), during which participants' neural activity was recorded via electroencephalography (EEG)
  - A **behavioral** (non-EEG) **enumeration task**, which served as a purer measure of enumeration fluency.
- The temporal acuity of event-related potential (ERP, a type of EEG) research makes it well-suited for studying rapid processes like enumeration.[4] Among commonly-studied ERP waveforms, the N400 has been established as a general marker of the recruitment of semantic knowledge, and is elicited in tasks involving non-symbolic quantities.[5,6]
- Numerosity-based differences in the N400 elicited during a visual enumeration task would suggest that semantic number knowledge is relevant for basic skills like determining quantity.

Methods

Participants:

- **19 adults** (12 female) over the age of 18
- Primarily college students and college staff, recruited via fliers and word of mouth
- All participants completed both the behavioral task and the ERP task.

Behavioral task:

- Arrays of **1-9 black dots** appeared on a gray screen *(Figure 1)*
- Participants reported how many dots they saw, as quickly and as accurately as possible, by pressing the corresponding number on a standard number pad
- Numerosities were presented in random order
- Dot size and density were both systematically varied to control for non-numerical perceptual features

Figure 1. Sample Stimuli for the Behavioral Task

Methods (cont.)

ERP task:

- 64-channel EEG nets (Electrical Geodesics, Inc.) recorded neural activity from the scalp
- Participants viewed arrays of 28 or 32 green and red dots *(Figure 2)*
  - Red = target dots to enumerate
    - Total number of red dots ranged from 0 to 6
      - **2, 3, and 4 dots** = numerosities of interest
    - Appeared either in left or right visual hemifield
      - 70 trials per numerosity per hemifield
  - Arrays were followed by a fixation cross, then a white digit
  - Participants pressed "Yes" or "No" buttons to indicate whether the digit matched the number of red dots
  - Electrode impedances were kept under 50 kΩ

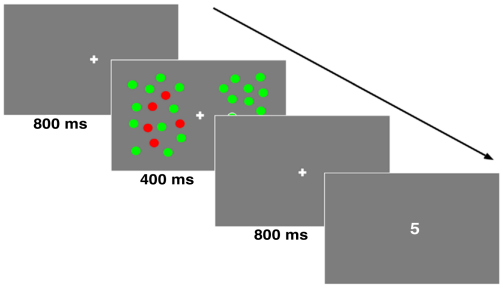

Figure 2. ERP task procedure with sample stimuli. *(Adapted from Pagano, Lombardi, & Mazza, 2014)*

Data Analysis

- **Counting Fluency** for each participant:
  - Slope across median reaction times for 5, 6, 7, and 8 dots (correct responses only)
  - Each participant was assigned to a **High** or **Low Counting Fluency** group based on a mean split (high fluency = flatter slope)
- **N400:**
  - EEG recordings were filtered to reduce electrical noise, and segments contaminated with physical artifacts were removed. Recordings were averaged across numerosity and hemifield.
  - **N400** was defined as the mean amplitude across **350-550ms** for **parietal** electrode groups
  - Data were submitted to a 3 (Numerosity: 2, 3, and 4) x 2 (Hemisphere: Contralateral and Ipsilateral) ANOVA to identify main effects and interactions
- **Links between Counting Fluency and N400:**
  - The **slope for N400 amplitudes** in the contralateral hemisphere across 2, 3, and 4 was calculated
  - A t-test compared N400 slopes between Low and High Counting Fluency groups

Results

N400 amplitude:

- Main effect of Numerosity, $F(2, 36) = 8.84$, $p < .001$ *(Figure 3)*
- Main effect of Hemisphere, $F(1, 18) = 6.03$, $p = .024$
- Numerosity*Hemisphere interaction $F(2, 36) = 11.72$, $p < .001$
  - In the contralateral hemisphere, but not the ipsilateral hemisphere, N400 amplitude decreased as numerosity increased *(Figure 4)*

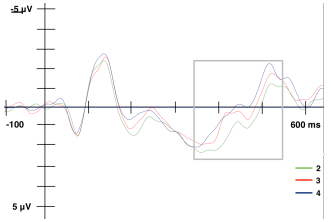

Figure 3. Grand-averaged N400 waveforms elicited for 2, 3, and 4 dots in the contralateral hemisphere.

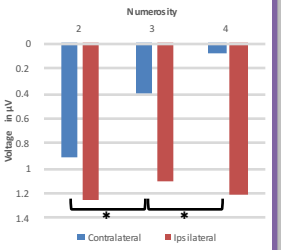

Figure 4. Mean N400 amplitudes for each numerosity and hemisphere.

Link to Counting Fluency:

- Compared to the High Counting Fluency group, the Low Counting Fluency group had a significantly steeper slope for contralateral N400 amplitude across numerosities, $t(17) = 2.21$, $p = 0.041$

Discussion

- Numerosity-based differences in N400 amplitude suggest that semantic knowledge is activated to a greater extent as the quantity of items to enumerate increases. Even basic tasks like enumeration may recruit number knowledge beyond rote skills.
- Modulation of the N400 in the contralateral hemisphere was greater for participants in the Low Counting Fluency group, who had weaker counting skills. It is possible that these individuals rely on number knowledge more than individuals with stronger counting skills.

References

1. Kaufman, E. L., Lord, M. W., Reese, T. W., & Volkmann, J. (1949). The discrimination of visual number. *The American Journal of Psychology, 62*(4) 498-525.
2. Aunio, P., & Niemivirta, M. (2010). Predicting children's mathematical performance in grade one by early numeracy. *Learning and Individual Differences, 20*(5), 427-435.
3. Pagano, S., Lombardi, L., & Mazza, V. (2014). Brain dynamics of attention and working memory engagement in subitizing. *Brain Research, 1543*, 244-252.
4. Mazza, V., & Caramazza, A. (2015). Multiple object individuation and subitizing in enumeration: a view from electrophysiology. *Frontiers in Human Neuroscience, 9*.
5. Paulsen, D. J., & Neville, H. J. (2008). The processing of non-symbolic numerical magnitudes as indexed by ERPs. *Neuropsychologia, 46*(10) 2532-2544.
6. Szűcs, D., & Csépe, V. (2004). Access to numerical information is dependent on the modality of stimulus presentation in mental addition: A combined ERP and behavioral study. *Cognitive Brain Research, 19*(1), 10-27.

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