Cognitive Underpinnings of Dyscalculia: Insights from Behavioral Modeling

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Abstract

Developmental dyscalculia (DD) is a learning disorder characterized by impairments in numerical and mathematical cognition. Despite its high prevalence and mental health impact, its cognitive origins and everyday life implications remain poorly understood. Here we test competing theories about cognitive impairments giving rise to DD using behavioral and neural data, positing either specific deficits in number perception or impaired working memory of magnitudes. We recruited 33 adolescents with DD and 33 neurotypical controls to complete a numerical magnitude comparison task during fMRI. Bayesian perceptual choice modeling revealed that individuals with DD did not show worse numerical perception precision, but poorer working memory when having to compare sequentially presented numerical magnitudes. Our data characterize numerical cognition deficits in DD and support (visio-spatial) working-memory accounts of the underlying cognitive impairments.

Keywords: Developmental dyscalculia, number sense, bayesian inference, perception, (visio-spatial) working memory

Background

Developmental dyscalculia (DD) is a math-specific learning disorder that cannot be explained by low intelligence or inadequate education. Although it affects 3–6% of the population—similar to dyslexia—and has a significant impact on daily life, its underlying causes and specific symptoms are not well understood. There is an ongoing debate about whether DD stems mainly from deficits in the approximate number system (ANS) (Mazzocco, Feigenson, & Halberda, 2011; Mussolin, Mejias, & Noël, 2010; Piazza et al., 2010), which helps us quickly estimate quantities, or from impairments in visuo-spatial working memory and other more domain-general attentional processes (Szucs, Devine, Soltesz, Nobes, & Gabriel, 2013).

This study aimed to clarify which neurocognitive mechanisms related to magnitude processing might be impaired in DD. To do so, we used a newly developed cognitive model of Bayesian perceptual inference, which assumes that numerical decisions result from integrating noisy sensory input and prior beliefs (Hollander, Grueschow, Hennel, & Ruff, 2024), with more prominent biases when numerical information is noisy. Importantly, given the choice architecture of our magnitude comparison task (sequential presentation of numerosities - see Fig. 1. left), the model enables us to distinguish between two types of noise related to basic number perception and working memory (Perceptual and memory based choice (**PMC**) model, Fig. 1. right).

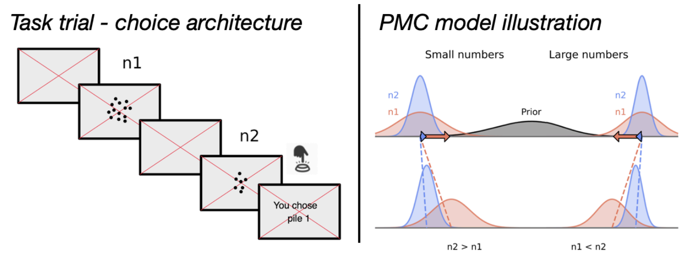

***Figure 1**: **Left**: Example trial of the Magnitude comparison task The two magnitudes (n1, n2) were presented as coin clouds (non-symbolically) one after the other, with a period of 6 to 9 seconds between them. Subjects could indicate the larger stimulus when the second magnitude was presented. **Right:** Number perception as a Bayesian inference process. Upper row: We assume that the likelihood dispersion for n1 (red) is influenced by both perceptual and memory noise, making it more dispersed than that of n2, which is primarily affected by perceptual noise (blue). These likelihoods are combined with the prior (gray - distribution over all possible numbers that are shown in the experiment). Therefore, the posteriors (lower row) are pulled towards the center of the distribution – in particular the posterior of memorized, noisier numerosities. This results in an over/under-estimation for small/large numbers.*

Results

We recruited 33 adolescents diagnosed (by a professional from the children's hospital) with DD and 33 neurotypical controls matched for age and gender (15-23 years, 28 females per group). Participants underwent fMRI while they performed the magnitude comparison task (fig. 1). Generally, DDs were slightly slower

(F(1,64)=3.93, p=0.052) but not significantly less accurate (F(1,64)=1.86, p=0.18) than controls in the task.

Psychophysical model. Psychophysical modeling showed no robust group differences in psychophysical slopes. There was a significant interaction between group and stimulus magnitude, with DDs showing a larger effect of overall magnitude on their choice (Fig. 2. C). This meant that on average, DDs were less likely to choose the second option for small magnitudes but more likely for large magnitudes (Fig. 2. B).

Cognitive model: Perceptual and memory based choice (PMC) model.

For a more mechanistic understanding of the above effects, we employed the PMC model, which explicitly models the noise in representations of the first and second option. Thus, both noise estimates contain basic perceptual noise, whereas the difference in the noise estimates reflects working memory noise. We found significantly different group distributions for both noise parameters (Fig. 2. D): Memory noise was larger for DDs, whereas perceptual noise was smaller.

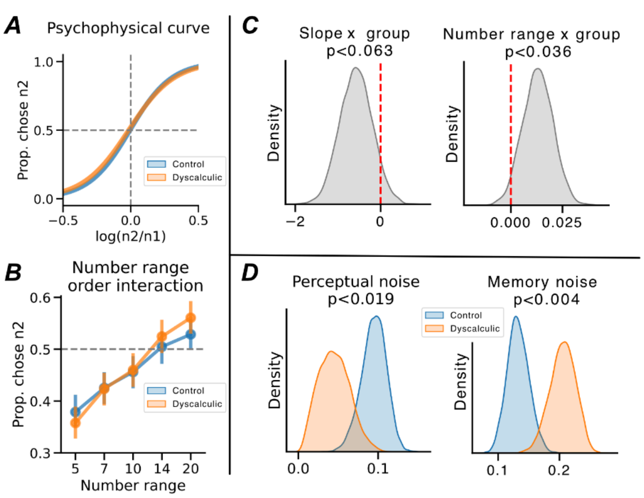

__Figure 2__: __A__: Average psychophysical choice curves of both groups. __B__: Magnitude effects of both groups. Note that for each range, the second option was larger 50% of the time. Any deviation from 50% is thus a bias. __C__: Posterior effect sizes of the psychophysical model of group on slope and number range order interaction (Bayesian p-values). __D__: Posterior group distributions from the PMC model for perceptual and memory noise (Bayesian p-values).

Discussion

While overall task accuracy was similar between groups, our cognitive model suggests that individuals with DD experience increased working memory noise, pointing to difficulties in maintaining and integrating numerical information—a pattern consistent with domain-general impairments in visuo-spatial working memory. Notably, we did not find evidence for increased perceptual noise, challenging the idea of a core deficit in the approximate number system (ANS).

Crucially, our cognitive model offers a novel approach by testing both accounts simultaneously - disentangling perceptual and memory-related noise within a unified framework. This allows for a more fine-grained understanding of how numerical decisions are formed and where specific impairments may arise.

The developmental context may also play an important role. Earlier studies reporting ANS deficits in DD had focused on younger children (e.g., Piazza et al., 2010), whereas our study—conducted with older participants—aligns with recent work in adolescents that also did not find a generalized magnitude deficit (McCaskey, Aster, Tuura, & Kucian, 2017). This suggests that the nature of DD may change with age, from early perceptual difficulties to later challenges with memory.

Our ongoing fMRI analyses will examine whether there is a neural surrogate to these DD-specific altered cognitive processes. Jointly employing cognitive and neural models that align in their general idea of how the brain processes certain information (numbers) might be a powerful approach to better understand different types of neurodivergences (dyscalculia).

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