ANS Acuity, Math Achievement, and Dyscalculia: Evidence for a Domain-specific Executive Function Relation

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Introduction

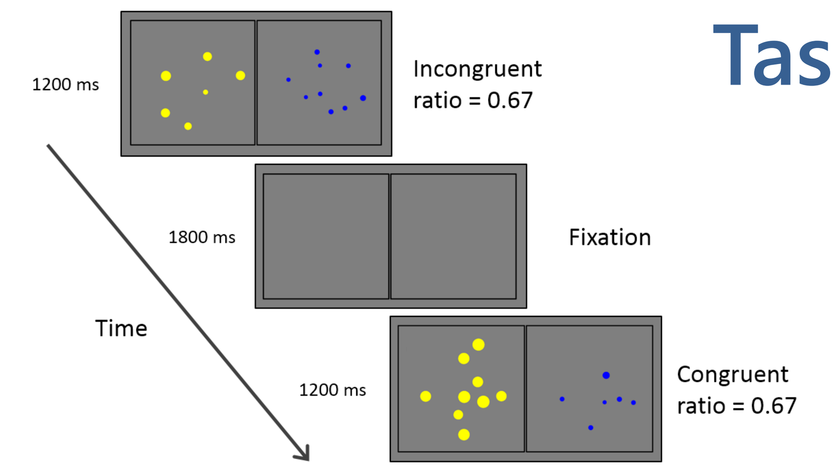
- Nonsymbolic number comparison tasks are thought to index the efficiency of neural systems used to perceive and manipulate (order, compare, add, and subtract) numerical magnitudes, often referred to as the approximate number system (ANS).[1]
- Both behavioral measures of ANS efficiency and associated neural activation patterns have been linked to math competence in typically and atypically developing individuals.[2,3,4]
- However, task performance is influenced by non-numerical visual parameters, such as surface area and size, and their congruency with the number of items in a set.[5,6,7]
- Trials with incongruent cues may require the inhibition of responses based on visual saliency to prioritize a quantity-based judgement, thereby increasing executive function (EF) demands.[6,7]
- The relation between number comparison performance and math competence may also depend on the task's measurement of EF.[8, 9, 10]
- To investigate, we conducted two analyses on a large sample of middle school students, (1) a group comparison analysis including a sample of individuals with developmental dyscalculia (DD) and (2) a regression analysis in the whole sample, where the relation between math competence and task performance was split by congruency condition.
- We hypothesized that number-specific EF, or *attention to number* (as indexed by incongruent trials on the number comparison task), would predict mathematics achievement beyond non-numerical measures of EF and ANS acuity alone.

Participants

- Participants were drawn from a longitudinal (Pre-K to 7th grade) study of students in a study of early math skills.
- English Language Learners (n = 23) were excluded from sample.
- Students were located in 76 public schools.
- 88.6% of sample qualified for free or reduced-price lunch.

	Achievement Groups (n = 222, 116 females)			Entire Sample (n = 448, 250 females)		
	Mean	SD	Range	Mean	SD	Range
Age (years), Pre-K	5.1	0.3	4.5-6.4			
Age (years), 6th grade	12.0	0.3	11.4-13.4	12.0	.32	11.4-13.4
Nonsymbolic Comparison (accuracy, %)	75.5	5.29	59-91	74.8	5.48	49-91
Backward Corsi (max span)	5.1	1.2	2-8	4.81	1.22	2-8
Hearts and Flowers (accuracy, %)	76.4	14.4	40-100	73.4	14.5	35-100
Letter-word ID – WCJ-III (K, percentile rank)	111.8	14.1	73-144	109.7	12.7	73-144
Math Achievement - KM-3 (6th grade, percentile rank)	42.1	22.7	1-93	27.0	23.1	1-93

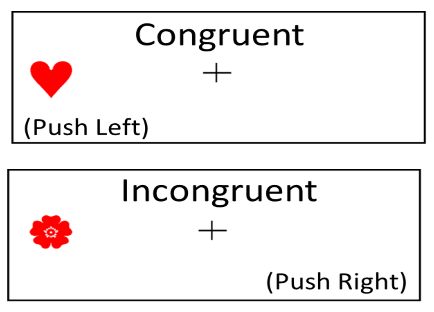
Tasks



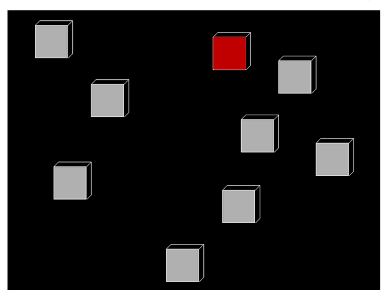
Nonsymbolic Number Comparison

- In congruent/congruent for convex hull, surface area, dot diameter, circumference, and density.[5]
- Ratios varied from 0.33 to 0.9.
- Dot count ranged from 5 to 15 per color.

Hearts & Flowers



Reverse Corsi Block Tapping



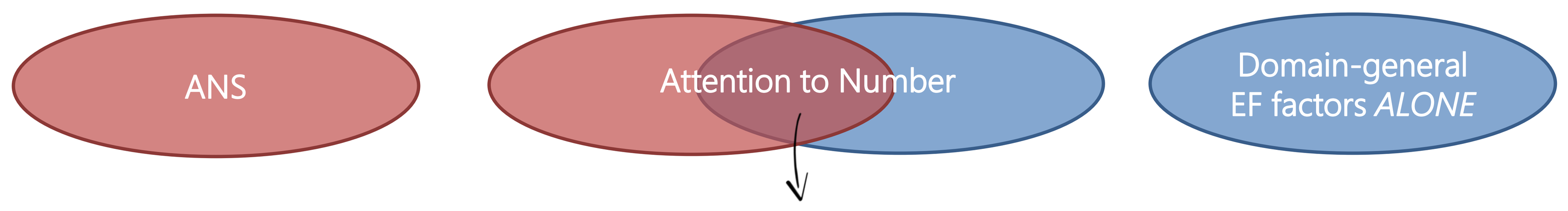
Methods

Study Questions: Is *attention to number* a factor related to math achievement beyond non-numeric EF and ANS acuity?

I. … as a factor distinguishing between achievement groups, characteristic of DD?
II. … across a wide range of math achievement?

Analysis I: Group comparison

a. Separate into dyscalculic (DD), low achieving (LA), and typically achieving groups (TA).
b. Compare performance on number comparison for congruent and incongruent trials.
c. Control for EF (inhibitory control, shifting, working memory), and reading.



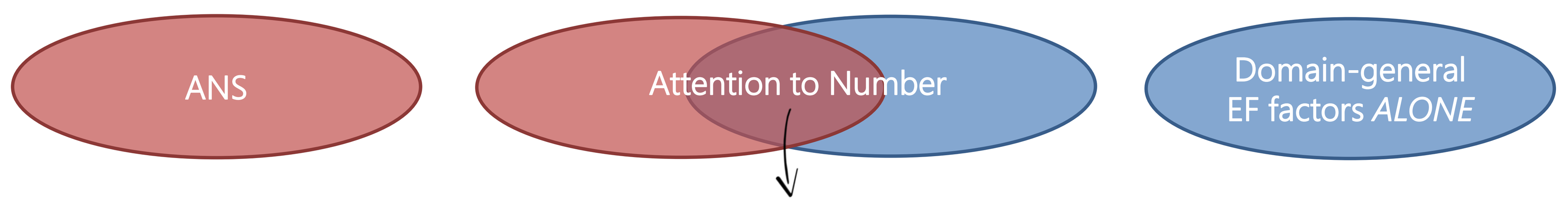
group differences on both congruent and incongruent trials of number comparison.

group differences on incongruent trials after controlling for EF.

no group differences on number comparison after controlling for EF.

Analysis II: Individual differences (regression).

a. Include whole group of n = 448.
b. Investigate relation between performance on number comparison and math achievement in 6th grade, split by congruency.
c. Control for EF (inhibitory control, shifting, working memory), age, and reading.



Individual differences on both congruent and incongruent number comparison.

Individual differences on incongruent trials after controlling for EF.

No Individual differences on number comparison after controlling for EF.

Results

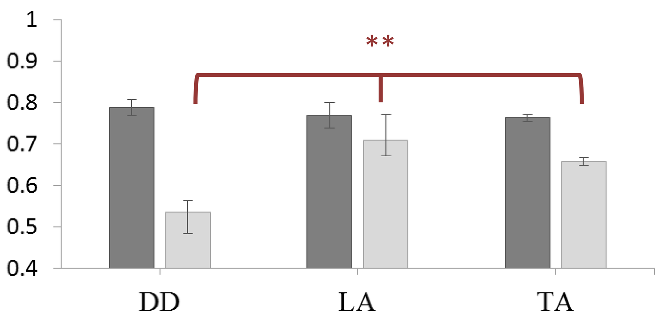
I. Group comparison

a.

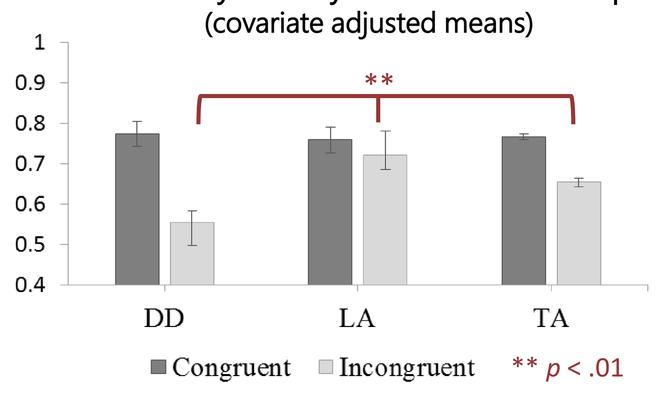
Achievement Groups	DD (n = 22, 7 females)			LA (n = 12, 6 females)			TA (n = 188, 106 females)		
	Mean	SD	Range	Mean	SD	Range	Mean	SD	Range
Age (years), 6th grade	12.2	0.5	11.4-13.4	12.0	0.3	11.6-12.5	12.0	0.3	11.4-12.6
Number Comparison (accuracy, %)	71.5	5.3	62.9-81.4	78.2	6.4	70.0-87.1	75.8	5.0	58.6-91.4
Backward Corsi (z-score of max span)	-1.21	1.22	-2.4-1.0	0.03	0.57	-0.9-1.0	0.37	0.85	-2.4-2.7
Hearts and Flowers (z-score of accuracy, %)	-1.29	0.79	-2.3-0.8	-0.16	0.83	-1.9-1.8	0.40	0.83	-1.9-1.8
Letter-Word ID (WCJ-III, standard score)	91.4	9.90	75-113	97.4	11.9	73-113	115.1	11.9	85-144

- No group differences for congruent trials [$F(2, 215) = .068$, $p = .935$, partial $\eta^2 = 0.001$] (ANCOVA)
- Group differences for incongruent trials [$F(2, 215) = 4.658$, $p = .010$, partial $\eta^2 = 0.042$] (ANCOVA)
- DD < TA [Bonferroni $p = .045$, Hedge's $g = 0.823$, adjusted means]
- DD < LA [Bonferroni $p = .005$, Hedge's $g = 0.585$, adjusted means]
- No difference between TA and LA on incongruent trials [$p = .231$]

b. Accuracy Rate by Achievement Group



c. Accuracy Rate by Achievement Group (covariate adjusted means)



II. Individual differences

- Accuracy on congruent trials does not correlate with math.
- Accuracy on incongruent trials correlates with math.
- Accuracy on incongruent trials is a significant predictor after controlling for EF, reading achievement, and age.

b. Bivariate correlations

Measure (n = 448)	1	2	3	4	5
1. Nonsymbolic Comparison, congruent trials, acc.					
2. Nonsymbolic Comparison, incongruent trials, acc.	-.447***				
3. Backward Corsi, max span	-.051	.193***			
4. Hearts and Flowers, mixed trials, acc.	.017	.186***	.242***		
5. Reading achievement, LWID, end of Kindergarten	-.010	.071	.130**	.172***	
6. Mathematics achievement, composite, grade 6	-.067	.226***	.396***	.411***	.412**

* p < .05, **p<.01, *** p < .0

c. Multi-level regression model

	6th grade math achievement ($\sqrt[3]{}$) M1	M2
Intercept	0.286** (0.091)	-1.084** (0.337)
Nonsymbolic Comparison, incongruent trials, acc.	0.321*** (0.066)	0.126* (0.050)
Nonsymbolic Comparison, congruent trials, acc.	0.097 (0.083)	
Backward Corsi, max span		0.050*** (0.007)
Hearts and Flowers, mixed trials, acc.		0.051*** (0.007)
Reading achievement, LWID, end of Kindergarten		0.005*** (0.001)
Age of KeyMath testing, 6th grade		0.007*** (0.002)

*p < .05, **p < .01, ***p < .001; (standard errors)

Discussion

- Analysis I indicated that accuracy rate on incongruent trials, and not congruent trials, of the nonsymbolic number comparison task is lower for DD than LA or TA groups, after controlling for EF and reading, supporting the hypothesis that an impairment in the interaction between EF and the ANS, or *attention to number*, is characteristic of groups trends in the DD sample.
- Analysis II likewise indicated that accuracy on incongruent trials, and not congruent trials, was associated with achievement, even after controlling for school membership, EF, reading achievement, and age, again supporting the *attention to number* hypothesis.
- Together, these analyses call into question the dominant theory linking ANS acuity and math achievement as well as alternative accounts that suggest the nonsymbolic number comparison task correlates with math achievement simply by measuring domain-general EF.
- Instead, the current results suggest that *attention to number*, elicited by attending to numerical stimuli amidst interference from non-numerical cues, relates to math achievement.
- In contrast, ANS acuity alone, as indexed by congruent trials of the number comparison task, does not relate to math achievement.
- Together, these findings suggest a need to reframe existing models of the relation between basic number processing and math competence and that educational interventions built on those models may be premature or misdirected.

References

1. Halberda, J., Mazzocco, M. M., & Feigenson, L. (2008). *Nature, 455*(October), 8–11.
2. Chen, Q., & Li, J. (2014). Acta Psychologica, 148, 163–72.
3. Schneider, M., et al.(2017). *Developmental Science, 20*(3), e12372
4. Mazzocco, M. M. M., Feigenson, L., & Halberda, J. (2011). *Child Development, 82*(4), 1224–1237
5. Gebuis, T., & Reynvoet, B. (2011). Behavior Research Methods, 43(4), 981–6.
6. Szűcs, D. et al. (2013). *Frontiers in Psychology, 4*(July), 444.
7. Fuhs, M. W., & McNeil, N. M. (2013). Developmental Science, 16(1), 136–48.
8. Gilmore, C. et al. (2013). PloS One, 8(6), e67374.
9. Bugden, S., & Ansari, D. (2015). Developmental Science, 5, 1–17.
10. Park, J., & Brannon, E. M. (2014). Cognition, 133(1), 188–200.
11. Räsänen, P., et al. (2009). Cognitive Development, 24(4), 450–472.

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