

BACKGROUND

1. Numerical distance effect (i.e. increasing latencies of number comparisons with decreasing differences between compared numbers) is considered as an evidence for analogue number representation [1].
2. Several lines of evidence show that processing multi-digit numbers goes far beyond single digit number processing and involves several other processes. Processes involved in multi-digit number processing leading to whole magnitude processing are referred to as decimal integration [2].
3. Different research approaches have been taken to study relationships between elementary numerical processing and math skill / expertise [3].
4. Especially several ways of defining math skill / expertise were used (see the graph below).

Calculation prodigies differ from controls not only in arithmetic skills
High arithmetic skills are not necessarily linked to the factors of high mathematical expertise. Skills are usually limited to arithmetic. Prodigies differ from general population in wide array of personality / mental health (e.g. Asperger syndrome).

Comparing students is not comparing high level experts
Mostly early year's students were recruited. This inclusion criteria in fact does not ensure examining high level math experts.

MATH SKILL / EXPERTISE

Usual math performance measures assess arithmetic skill not math
The utilized tasks may simply measure processing automaticity since they comprise abilities being part of obligatory math curriculum.

Studying professional mathematicians
Professional mathematicians differ qualitatively from general population in math expertise. They differ from prodigies as well.

Objectives of the presented study

Comparing three groups:

1. Professional mathematicians.
2. Professionals who use advanced mathematics in their work but are not mathematicians per se.
3. Matched controls.

We aimed to compare elementary number magnitude processing (distance effect in single-digit numbers) and processing of two-digit numbers (decimal integration).

References:

- [1] Holloway, I. D., & Ansari, D. (2009). Mapping numerical magnitudes onto symbols: The numerical distance effect and individual differences in children's mathematics achievement. *Journal of experimental child psychology*, 103(1), 17-29.
[2] Nuerk, H.-C., Moeller, K. & Willmes, K. (2014). Multi-digits numerical understanding. In R Cohen Kadosh & A Dowker (Eds.). *Oxford Handbook of Mathematical Cognition*, Oxford University Press, Oxford, UK.
[3] Cipora, K., & Nuerk, H. C. (2013). Is the SNARC effect related to the level of mathematics? No systematic relationship observed despite more power, more repetitions, and more direct assessment of arithmetic skill. *The Quarterly Journal of Experimental Psychology*, 66, 1974-1991.
[4] Masson, M. E. (2011). A tutorial on a practical Bayesian alternative to null-hypothesis significance testing. *Behavior research methods*, 43(3), 679-690.

METHOD

Participants

N = 44 (6 F); Mean age = 27.9 (SD = 1.1).
Advanced doctoral students 3rd year or higher.
All right-handed, native Polish speakers.

3 groups:

1. Mathematicians [M] (n = 14; 2F).
2. Engineers [E] (professionals who use advanced math in their work; n = 15; 2F).
3. Controls [C] (studies in the field of humanities and social sciences; n = 15; 2F).

Materials and procedure

Magnitude classification

Numbers 1,2,3,4,6,7,8,9 were classified as larger or smaller than 5.
2 blocks with reversed response keys assignment (each number presented 30 times / block).

Number comparison

- Choose larger number; 180 trials; Conditions:
 - Unit decade compatibility (e.g. 21 98 vs 29 91)
 - Decade distance (small: 1-3; large > 3; within decade)
 - Unit distance (small 1-3; large > 3)

Order of administration

1. Parity judgment (not reported).
2. One-digit number magnitude classification and two-digit number comparison.
3. fMRI study (not reported).
4. Raven Advanced Matrices [RPM-A].

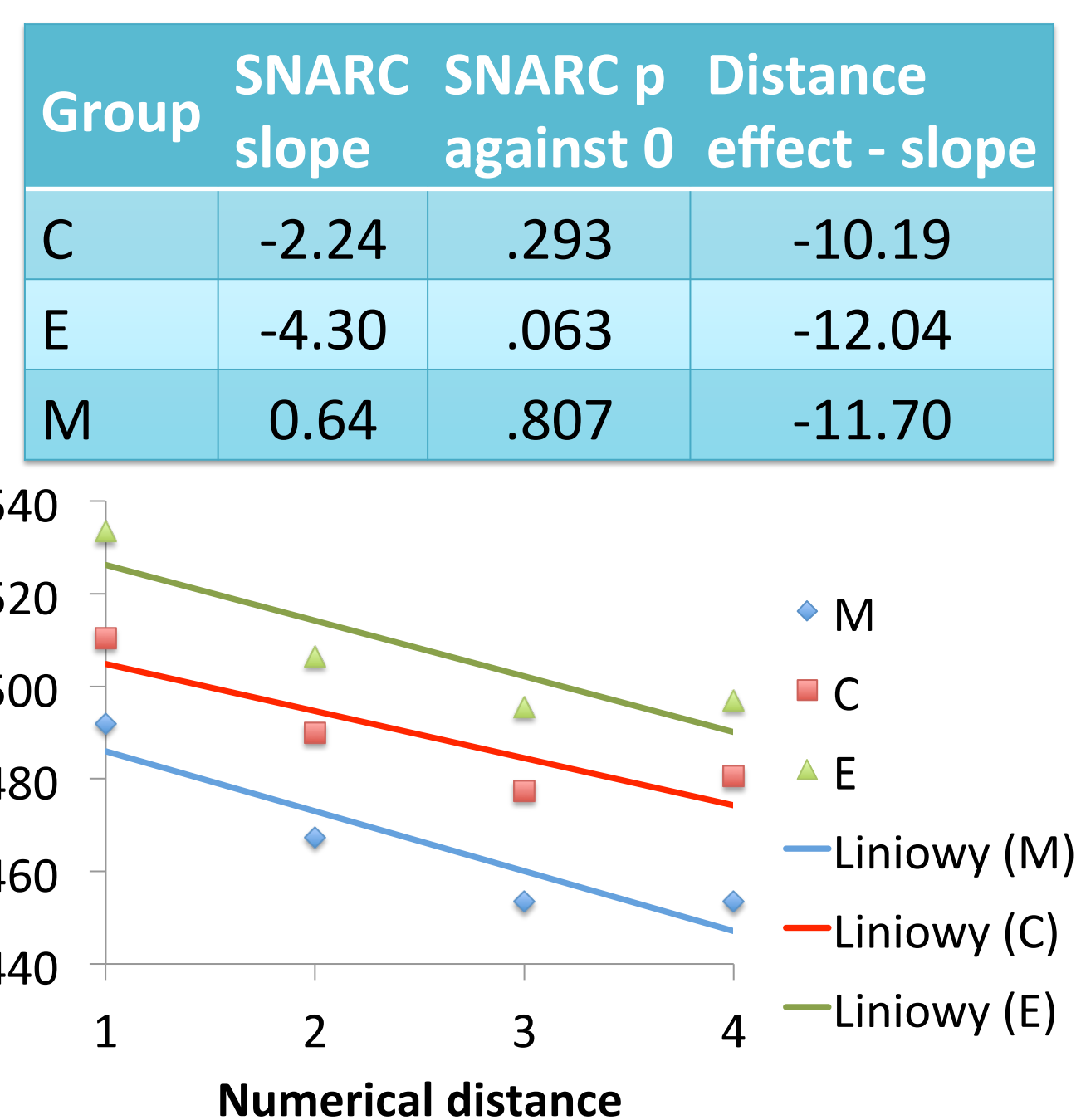
Accuracy measures [ACC] – Arcsin (square root of error proportion)

RESULTS

Single digit number processing

SNARC effect

- SNARC effect not present neither at the sample level nor in any group (table).
- Present when C and E groups taken together slope = -3.23; $p = .035$.
- No group difference in slopes ($F_{2,39} = 1.19$; $p = .315$). Bayesian analysis [4]: .93 probability for no difference.



Numerical distance

Single digit numbers

- Sample level: in RTs and in ACC (p 's < .001)
- RT's No group difference in distance slopes ($F < .05$). Bayesian analysis: .96 probability for no difference.
- ACC [3 (group) \times 4 (distance) ANOVA]: No main effect of group ($p = .923$) nor group \times distance interaction ($p = .168$).
- No correlations (slope & ACC) with RPM-A (r 's < .15; p 's > .419).

Multidigit numbers

- Mean slope -2.44 ($p < .001$)
- Group difference [M = -2.56; E = -2.73; C = -2.05; $p = .045$; $\eta^2 = .14$]
- No correlation with RPM-A ($r = .26$; ns)

Multidigit number processing

Reaction times [no correlations with RPM-A]

Unit decade compatibility

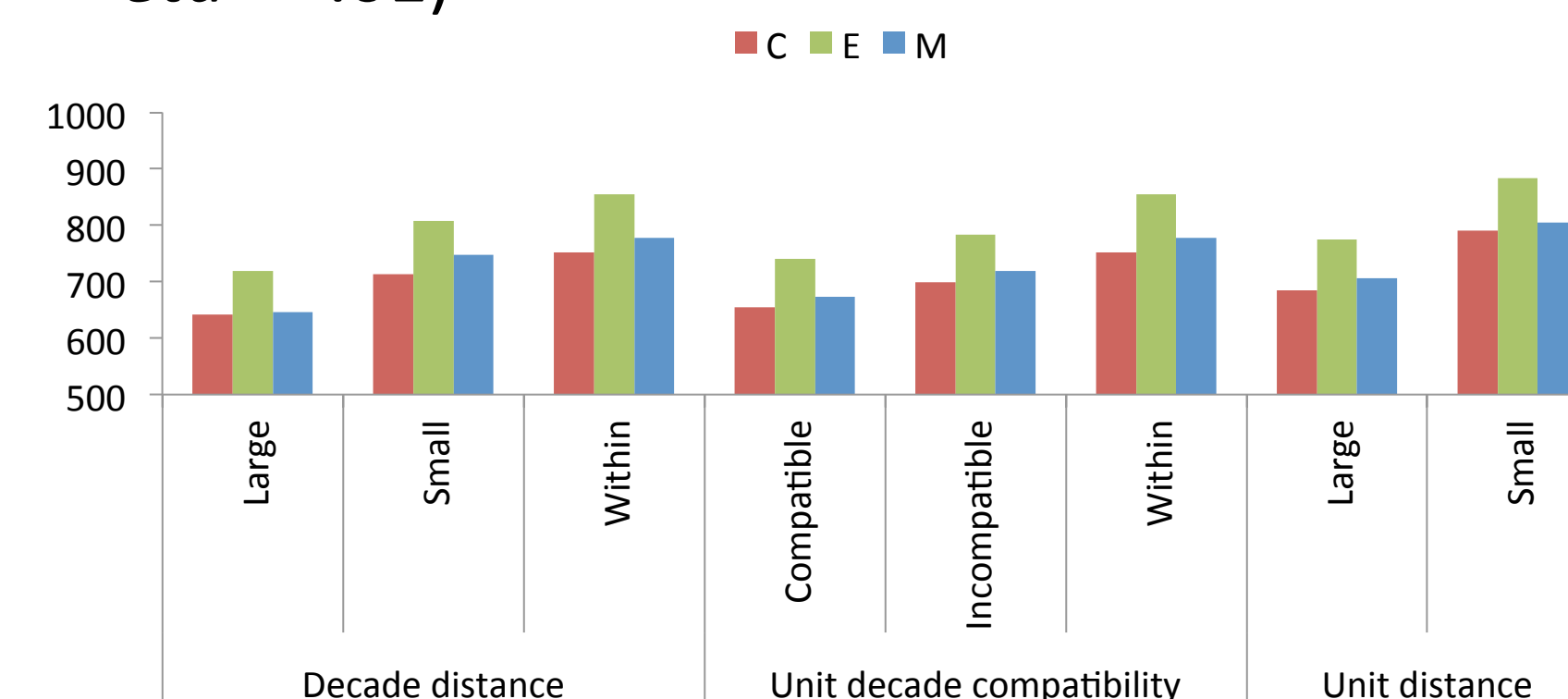
- Compatibility ($p < .001$; $\eta^2 = .84$)
- Group ($p = .038$; $\eta^2 = .15$)
- No group \times compatibility ($p = .510$; $\eta^2 = .04$)

Decade distance

- Decade distance ($p < .001$; $\eta^2 = .87$)
- Group ($p = .038$; $\eta^2 = .15$)
- No group \times decade distance ($p = .105$; $\eta^2 = .09$)

Unit distance

- Unit distance ($p < .001$; $\eta^2 = .90$)
- Group ($p = .043$; $\eta^2 = .14$)
- No group \times unit distance ($p = .752$; $\eta^2 = .01$)



Accuracies [correlations with RPM-A see table]

Unit decade compatibility

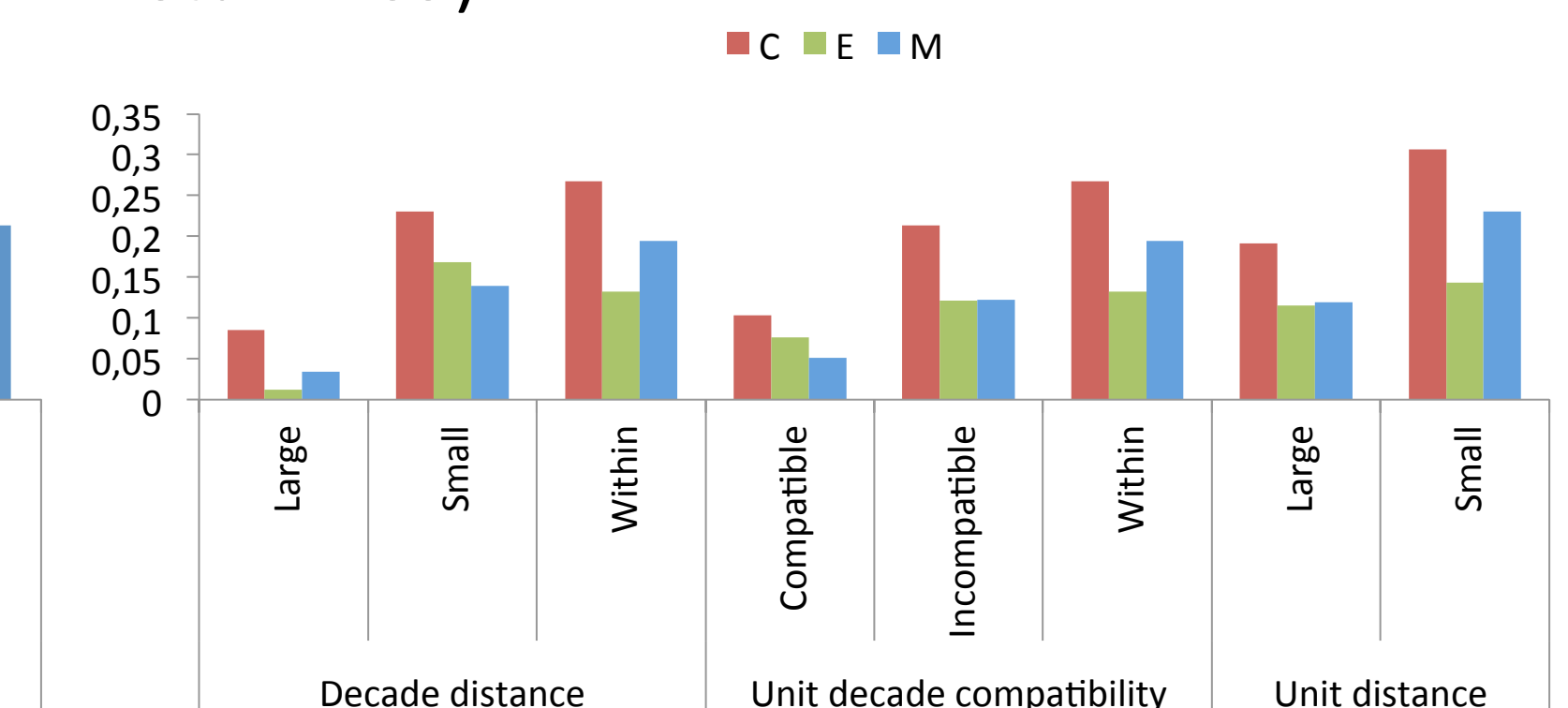
- Compatibility ($p < .001$; $\eta^2 = .34$)
- Group ($p = .006$; $\eta^2 = .22$)
- No group \times compatibility ($p = .156$; $\eta^2 = .08$)

Decade distance

- Decade distance ($p < .001$; $\eta^2 = .58$)
- Group ($p = .003$; $\eta^2 = .25$)
- No group \times decade distance ($p = .136$; $\eta^2 = .08$)

Unit distance

- Unit distance ($p < .001$; $\eta^2 = .30$)
- Group ($p = .006$; $\eta^2 = .22$)
- No group \times unit distance ($p = .161$; $\eta^2 = .09$)



CONCLUSIONS

1. Mathematicians do not differ from other groups in single digit number processing.
2. Similarly to other groups Mathematicians possess analogue representation of single digit numbers.
3. Absence of the SNARC effect may be caused by power issues (in E and C groups when analysed separately). At the sample level – by lack of SNARC in M group.
4. Between group differences appear in case of processing multi digit numbers. Between group differences are more pronounced in accuracies than in RT's.
5. Participants obtaining higher scores in Raven Matrices are characterized with more efficient decimal integration.
6. Raven score correlates with efficiency of decimal integration, especially with performance in conflict conditions. It does not correlate with single digit numbers processing.

Take home message

Expert mathematicians do not differ from controls in respect of analogue magnitude representation of single digit numbers but they are more efficient in processing multi digit numbers.

Accuracies	RPM-A
In total	-.18
Unit-decade compatible	-.10
Unit-decade incompatible	-.35
Within decade	-.02
Large decade distance	-.34
Small decade distance	-.22
Large unit distance	-.35
Small unit distance	.13
	$p < .05$