



HAL
open science

Evidence for the role of inhibition in numerical comparison: A negative priming study in 7- to 8-year-olds and adults

Arnaud Viarouge, Olivier Houdé, Grégoire Borst

► **To cite this version:**

Arnaud Viarouge, Olivier Houdé, Grégoire Borst. Evidence for the role of inhibition in numerical comparison: A negative priming study in 7- to 8-year-olds and adults. *Journal of Experimental Child Psychology*, 2019, 186, pp.131-141. 10.1016/j.jecp.2019.05.011 . hal-02920291

HAL Id: hal-02920291

<https://hal.science/hal-02920291>

Submitted on 25 Oct 2021

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution - NonCommercial 4.0 International License

1

2

Evidence for the role of inhibition in numerical comparison: a

3

negative priming study in 7-8-year-olds and adults

4

Arnaud Viarouge^{1,*}, Olivier Houdé^{1,2}, Grégoire Borst^{1,2}

5

6

¹Université de Paris, LaPsyDÉ, CNRS, F-75005 Paris, France.

7

²Institut Universitaire de France

8

9

Word count: 6201

10

Number of Figures: 3

11

Number of Tables: 2

12

13

Declarations of interest: none

14

15

*Corresponding author

16

Dr. Arnaud Viarouge

17

Université de Paris

18

Laboratory for the Psychology of Child Development and Education (LaPsyDÉ, UMR8240)

19

46 Rue Saint Jacques

20

75005 Paris, France

21

E-mail address: arnaud.viarouge@parisdescartes.fr

22

Phone : +33 1.40.46.29.95

1 **Introduction**

2 Research on numerical cognition has identified basic systems of numerical processing
3 (Feigenson, Dehaene, Spelke, 2004). One of them, the approximate number system (ANS)
4 (Halberda & Feigenson, 2008), allows us to estimate the number of objects in a set, providing
5 us with a sense of discrete quantity (Dehaene, 1997). Many studies have investigated the
6 characteristics of numerical estimation and its development (Dehaene, 2003; Cantlon,
7 Brannon, Carter, & Pelphey 2006; Halberda & Feigenson, 2008). In general, these studies
8 use the non-symbolic numerical comparison task, whereby participants perform numerical
9 comparative judgments between two rapidly presented dot arrays. In such a comparison task,
10 performance depends on the ratio between the two presented numerosities (i.e., the quantity
11 represented by a set of objects), the ANS following Weber's law (Piazza, Izard, Pinel, Le
12 Bihan, & Dehaene, 2004). One difficulty researchers face when using this task resides in the
13 continuous, non-numerical dimensions of magnitude (size, total surface area, density, etc.)
14 that one can perceive in the stimuli. These continuous dimensions can affect numerical
15 judgments throughout development (Rousselle, Palmers, & Noël, 2004; Szűcs, Nobes,
16 Devine, Gabriel, & Gebuis, 2013; Tokita & Ishiguchi, 2013) and adulthood (Gebuis &
17 Reynvoet, 2012a, 2012b; Gebuis, Cohen Kadosh, & Gevers, 2016).

18

19 *Inhibiting the irrelevant dimensions to focus on number*

20 One of these continuous dimensions is spatial extent. Since Piaget's seminal work on the
21 influence of length on numerical abilities in children (Piaget, 1952), behavioral and brain
22 imaging studies have shown evidence of interactions between number and spatial extent that
23 are present very early in infancy (de Hevia, Izard, Coubart, Spelke, & Streri, 2014; Pinel,
24 Piazza, Le Bihan, & Dehaene, 2004; see Hubbard, Piazza, Pinel, & Dehaene 2005, for a
25 review). These interactions have been reported in various studies in adults. For instance,

26 perceiving Arabic digits can bias estimation of sizes (de Hevia, Girelli, Bricolo, & Vallar,
27 2008; Viarouge & de Hevia, 2013) and relative conceptual size (e.g., pictures of an elephant
28 vs. a dog) can affect parity judgments (Gabay, Leibovich, Henik, & Gronau, 2013).
29 Several studies have investigated the impact of size on symbolic numbers using the size
30 congruity (or numerical Stroop) task (Arend & Henik, 2015; Henik & Tzelgov, 1982;
31 Leibovich, Diesendruck, Rubinsten, & Henik, 2013; Pavese & Umiltà, 1999; Schwarz &
32 Ischebeck, 2003), in which the participants' performances decrease when a numerical
33 comparison is made between two Arabic digits with incongruent sizes (e.g., 6 vs 9).
34 The number/size congruency effect has also been found in non-symbolic numerical
35 comparison tasks (Nys & Content, 2012; Hurewitz, Gelman, & Schnitzer, 2006). For
36 instance, Hurewitz and collaborators (2006) reported lower performances in adults when the
37 sizes of the presented items were incongruent with their number (i.e, the set with larger dots
38 was less numerous), than when they were congruent or neutral. Similar congruency effects
39 have been observed in the context of non-symbolic numerical comparison tasks in
40 preschoolers and school-aged children (Defever, Reynvoet, & Gebuis, 2013; Fuhs & McNeil,
41 2013; Fuhs, McNeil, Kelley, O'Rear, & Villano, 2016; Gilmore, Cragg, Hogan, & Inglis,
42 2016; Szűcs, Nobes, Devine, Gabriel, & Gebuis, 2013). While most studies in preschoolers
43 report congruency effects on accuracy rates (Fuhs & McNeil, 2013; Fuhs et al., 2016), studies
44 in early primary school years report both less accurate and slower responses on incongruent
45 trials whereby dot area and/or total surface area of the dots were among the manipulated non-
46 numerical dimensions (Gilmore et al., 2013; Szűcs et al., 2013).
47 Several studies have investigated the development of these congruency effects with age,
48 showing that age influences the amplitude of the difference in performance between
49 congruent and incongruent trials in non-symbolic numerical comparison tasks (Defever et al.,
50 2013; Gebuis, Herfs, Kenemans, de Haan, & van der Smagt, 2009; Soltész, Szűcs, & Szűcs,

2010; Szűcs et al., 2013). In particular, studies have reported larger congruency effects between school-aged children and adults. For instance Szűcs and colleagues (2013) found a larger congruency effect in 7-year-olds compared to adult participants, in a non-symbolic numerical comparison task whereby numerosity could be either congruent or incongruent with several non-numerical dimensions including dots' average size and total surface area. Consistent with studies suggesting that congruency effects could reflect the role of inhibition in numerical comparison tasks (Fuhs & McNeil, 2013; Fuhs et al., 2016; Rousselle & Noël, 2008), Szűcs and colleagues propose that larger congruency effect in children could be due to lower inhibitory control abilities (see also Defever et al., 2013 for a similar account). This is consistent with the protracted development of inhibitory control from childhood to late adolescence (Luna, Padmanabhan, & O'Hearn, 2010).

Recently, several authors have gone so far as proposing that inhibitory control is necessary for numerical development (Clayton & Gilmore, 2015; Leibovich, Katzin, Harel, & Henik, 2017, Szűcs et al., 2013), either to develop numerical representations from a general sense of magnitude (Leibovich et al., 2017) or to handle the interference between an innate sense of number and the continuous dimensions of magnitude at all ages (Clayton & Gilmore, 2015; see Cappelletti, Didino, Stoianov, & Zorzi, 2014 for a study in aging).

However, a few studies have failed to observe congruency effects, casting doubt on the critical causal role of inhibitory control in non-symbolic numerical comparison. For instance, Odic, Libertus, Feigenson, & Halberda (2013), and Odic, Hock, & Halberda (2014) failed to observe lower performance in trials in which number was incongruent with total cumulative area, than in trials in which it was congruent, in children or in adults.

In order to clarify the role of inhibition in numerical development, it is crucial to precisely evaluate the impact of inhibitory control processes in numerical comparison tasks. So far, the efficiency to block irrelevant dimensions of magnitude in the stimuli has been assessed either

76 through a posteriori analyses of performances in incongruent trials (Fuhs & McNeil, 2013;
77 Gilmore et al., 2013) or via correlational analyses using seminal inhibitory control tasks (e.g.,
78 the inhibition subtest of the NEPSY-II, Keller & Libertus, 2015).

79

80 *The current study*

81 In the current study, we took a different approach to provide evidence for or against the role
82 of inhibitory control in numerical comparison tasks in 7-8-year-olds and adults, by devising a
83 negative priming paradigm. The logic of the negative priming paradigm is as follows: if one
84 needs to inhibit irrelevant information or distractors on a given incongruent item (i.e., the
85 prime), the processing of that information (or distractor) on a subsequent congruent item (i.e.,
86 the probe) should be impaired (i.e., longer response times or higher error rates) as compared
87 to a control condition in which the information to process on the probe is not related to the
88 one to process (or to inhibit) on the prime (see Tipper, 2001). This paradigm, initially used by
89 Tipper (1985) to study inhibitory control processes at play in selective attention, was later
90 adapted to demonstrate the role of inhibition in various tasks, from classic color-word Stroop
91 tasks (Dalrymple-Alford & Budayer, 1966; Pritchard & Neumann, 2009) to logico-
92 mathematical reasoning tasks such as Piaget's number-conservation task (Borst, Moutier, &
93 Houdé, 2013; Houdé & Guichart, 2001). To provide evidence that a non-numerical
94 dimension of magnitude (i.e., size) needs to be inhibited to process numerosity in both 7-8-
95 year-olds and adults, we adapted a numerical comparison task to a negative priming
96 paradigm. Previous studies have shown that, in experimental contexts with such explicit
97 congruence/incongruence between number and non-numerical dimensions of magnitude,
98 preschoolers' performance could be very low on incongruent trials (Soltész et al., 2010).
99 Given that negative priming effects can only be observed if incongruent prime trials are
100 performed correctly, we chose to test primary school children. This also ensured that we

101 would be able to base our analyses of negative priming on both accuracy levels and reliable
102 reaction times, as is usually the case in the negative priming literature (Tipper, 2001; Neill,
103 Valdes, & Terry, 1995; Borst, Poirel, Pineau, Cassotti, & Houdé 2013). If both 7-8 year-olds
104 and adults need to inhibit the irrelevant dimension of size when comparing numerosities in
105 incongruent items (i.e., dot array with more dots is smaller than the dot array with less dots
106 and thus size interferes with number), they should require more time and commit more errors
107 when congruent items (i.e., dot array with more dots is larger than the dot array with less
108 dots) are preceded by incongruent items than by neutral items (i.e., the two dot arrays have
109 identical size).

110 Given the protracted development of inhibitory control until late childhood and adolescence
111 (Luna et al., 2010), and following our hypothesis of a causal link between inhibitory control
112 and numerical comparison abilities, we should observe differences in the amplitude of the
113 negative priming effects in the context of the non-symbolic numerical comparison task
114 between our two age groups. Previous studies have shown that the amplitude of the negative
115 priming effect could reveal the efficiency of the inhibitory control processes at play in a
116 given context, by comparing primary school children and adults (e.g., Aïte et al., 2016; Borst,
117 Poirel, et al., 2013). In other words, if numerical comparison abilities are rooted in part on the
118 ability to inhibit an irrelevant non-numerical dimension of size, then the amplitude of the
119 negative priming effect should be smaller in 7-8-year-olds than in adults, due to lower
120 inhibitory control abilities in children than adults.

121

122 **Method**

123 *Participants*

124 Forty-seven primary school children (23 girls and 24 boys, mean age = 7.92 years, SD =
125 .87) and thirty-two adults (21 females and 11 males, mean age = 27.86 years, SD = 6.13) with

126 normal or corrected-to normal vision, participated in this study. The proportion of males to
127 females did not differ between the two groups, $\chi^2(1) = 2.15$, $p = .21$. Children were recruited
128 in primary schools, and participated voluntarily after their parents gave informed consent.
129 Adult participants were recruited through a mailing list. They gave informed consent and
130 received 5 euros for their participation to the study. All participants were tested in accordance
131 with national and international norms that govern the use of human participants.

132

133 *Materials and Procedure*

134 *Numerical Comparison Task Adapted to a Negative Priming Paradigm*

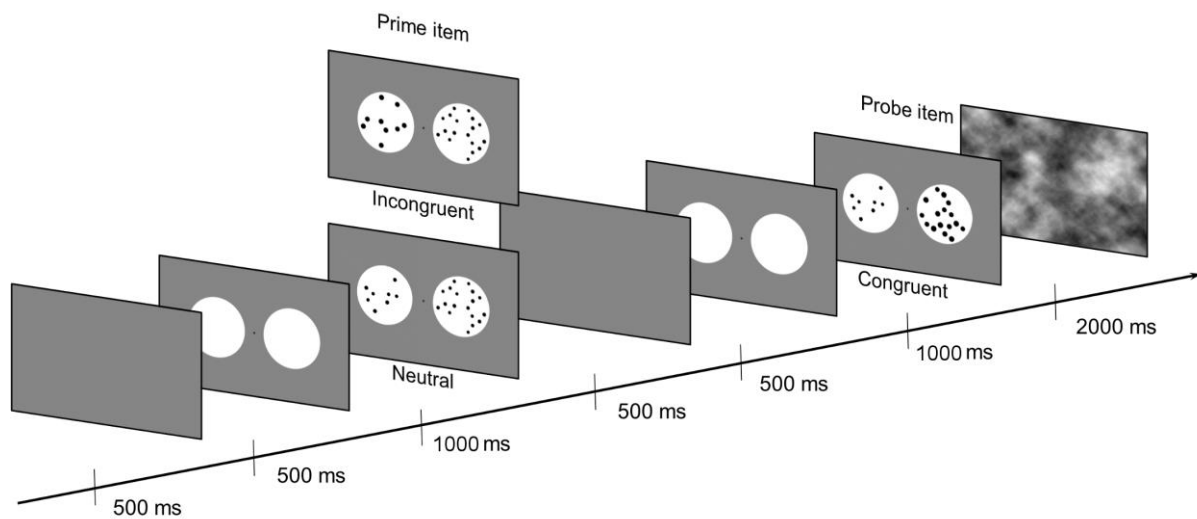
135 The task stimuli were pairs of dot arrays, generated using Matlab and presented on the left
136 and right side of the computer screen. The participants were seated approximately 50 cm
137 from the screen. Each array of black dots was presented on a white circle (diameter visual
138 angle of 8°) at a visual angle of 5.3° from a central-fixation cross. The sets of dots were
139 generated using the *Number*, *Size* and *Spacing* dimensions as defined by DeWind and
140 colleagues (DeWind, Adams, Platt, & Brannon, 2015). This allowed us to manipulate the
141 congruency between *Number* and *Size* while keeping the *Spacing* dimension constant. *Size* in
142 both arrays were either identical (neutral item), congruent (congruent items) or incongruent
143 with the number of dots (incongruent items). We used a 1:2 numerical ratio (8 vs. 16 or 9 vs.
144 18 dots) in prime items (i.e., neutral and incongruent items) to ensure a high level of
145 performance which is needed to run the analyses of the negative priming effects on the probe
146 items. We presented 4:5 (12 vs. 15 dots) and 5:6 (10 vs. 12 dots) numerical ratios on the
147 probe items (i.e., congruent items). These ratios were chosen so that the difficulty level would
148 vary across the trials while keeping the total duration of the experiment acceptable for
149 children (~5 min). For the incongruent and congruent items, following Salti, Katzin, Katzin,
150 Leibovich, & Henik (2017), we controlled the saliency of the non-numerical dimension

151 relative to the numerical dimension, i.e. the level of participants' reliance on non-numerical
152 dimensions across trials, by equating the non-numerical ratio between two sets of dots to their
153 numerical ratio. Specifically, the *Size* ratio was always in a 1:3 ratio with the numerical ratio
154 (e.g. when the sets of dots are in a 1:2 numerical ratio, the *Sizes* in each set are in a 1:6 ratio,
155 and when the numerical ratio is 4:5, the *Size* ratio is 4:15). For neutral prime items, *Size* was
156 approximately halfway between the *Size* of the less numerous and more numerous arrays
157 across the congruent and incongruent items. Across all the items, the dot array pairs were
158 generated so that the percent difference in the occupied field area (defined by the minimum
159 bounding circle) between the two arrays was less than 10%. Each trial consisted in a prime-
160 probe item pair. Incongruent prime items followed by a congruent probe item will be further
161 referred to as the test trials, whereas neutral prime items followed by a congruent probe item
162 will be referred to as the control trials. Each trial type (test and control) was presented 24
163 times (12 per numerical ratio). We added 8 filler trials consisting of the following
164 combinations of prime and probe items (one for each of the two numerical ratios used on the
165 probe items: congruent /incongruent, incongruent /incongruent, incongruent /neutral and
166 neutral/incongruent) to prevent the participants from noticing the pattern of incongruent,
167 neutral and congruent items between the prime and probe. Thus, participants performed 56
168 experimental trials (112 items) presented in a random order.

169

170 The participants were instructed to press one of two keyboard keys ("D" or "K") on the side
171 of the more numerous array as quickly and accurately as possible. Each trial started with a
172 gray screen (500 ms), followed by a fixation cross and two white circles (500 ms). The arrays
173 of dots from the prime item were then presented in the white circles until the participant gave
174 a response, for a maximum duration of 1000 ms, at which time they were replaced by a gray
175 screen. As soon as the participant gave their response, the same series of events occurred for

176 the probe item. A mask was presented for 2000 ms as soon as the participants provided a
 177 response on the probe item to prevent transfer of processes between the probe and the prime
 178 of the next trial (Figure 1).



179

180 **Figure 1: Adaptation of the non-symbolic comparison task to a negative priming paradigm.**
 181 Sequences of events in a test and control trial of the numerical comparison task.

182

183 The total duration of the task was approximately 5 minutes. The experiment started with 4
 184 training trials (2 test and 2 control trials), using 1:2 numerical ratios for all of the items
 185 presented and a feedback on the accuracy of the participants' response was provided.

186

187

188 **Results**

189 The data for one child was removed due to technical failure. We first removed individual
 190 trials with RTs differing by two standard deviations from the average individual RT on either
 191 the prime or probe items of the control or test trials, which corresponded to 6.7% of the total
 192 number of trials across all participants in the children group, and 7.9% of the total number of
 193 trials across all participants in the adults group. For each participant, we averaged the

194 proportion of correct responses and the response times (RTs) on items correctly performed,
 195 separately on the prime and the probes of the control and the test trials. The data from three
 196 additional children and two adults were removed due to overall accuracy rates (ARs) more
 197 than two standard deviations below their age group's average, leading to a final analyzed
 198 sample of 43 children and 30 adults. We verified that all the analyses described below
 199 remained identical when including these participants back into the sample. We then
 200 combined RTs and ARs by computing an inverse efficiency score (IES, Townsend & Ashby,
 201 1978; 1983), i.e. by dividing participants' average RTs by their average ARs on the prime
 202 and the probe items of the control and test trials. Note that in accordance with the logic of the
 203 Negative priming paradigm, we only analyzed ARs, RTs and IES on the probe items
 204 preceded by prime items performed correctly.

205

206 *Congruency Effects on the Prime items*

207 In order to test for the presence of a congruency effect in the prime items, we first ran a 2 age
 208 group (Children vs. Adults) x 2 congruency (Incongruent vs. Neutral) repeated measures
 209 ANOVA on the IES (see Table 1 for descriptive statistics on the prime items).

210

211

212

213 Table 1

214 *Average and range of ARs and RTs (ms) for the incongruent and neutral prime items of the*

215 *non-symbolic numerical comparison task*

	7-8-year-olds		Adults	
	M (SD)	Range	M (SD)	Range
Incongruent prime items				
Ars	0.88 (0.12)	0.54 - 1	0.99 (0.04)	0.77 - 1

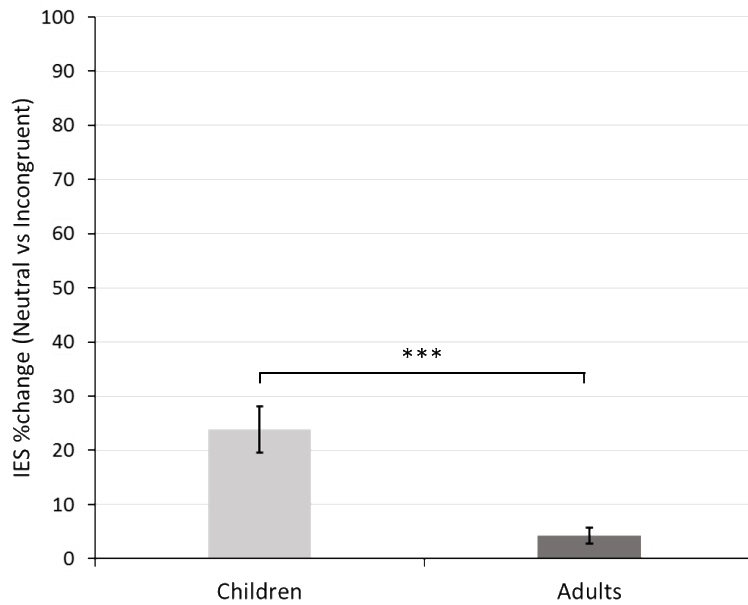
RTs	784 (223)	493 - 1661	492 (74)	349 - 685
Neutral prime items				
Ars	0.97 (0.05)	0.72 - 1	0,99 (0.02)	0.88 - 1
RTs	710 (175)	479 - 1397	475 (62)	358 - 633

216

217 The analysis showed a main effect of age group, $F(1, 71) = 49.02, p < .0001, \eta^2_p = 0.41$, with
 218 lower IES in the adult group ($M = 487, SD = 204$) than in the children group ($M = 827, SD =$
 219 204). The analysis also revealed a main effect of congruency, $F(1, 71) = 17.48, p < .0001, \eta^2_p$
 220 $= 0.2$, with lower IES for the neutral items ($M = 607, SD = 147$) than for the incongruent
 221 items ($M = 708, SD = 292$). We also observed a significant interaction between congruency
 222 and age group, $F(1, 71) = 11.17, p = .001, \eta^2_p = 0.14$.

223 We then ran paired t-tests between the incongruent and neutral trials on both age groups
 224 separately. IES was significantly higher for the incongruent condition than for the neutral
 225 condition both for children (incongruent: $M = 918, SD = 368$; neutral: $M = 736, SD = 181$),
 226 $t(42) = 4.55, p < .0001, d = 0.934$, and adults (incongruent: $M = 498, SD = 76.2$; neutral: $M =$
 227 $477, SD = 63$), $t(29) = 2.64, p = .01, d = 0.523$. Finally, we computed a percentage change in
 228 IES between neutral and incongruent items to compare the congruency effect between
 229 children and adults while controlling for overall difference in IES. A t-test confirmed that the
 230 congruency effect was larger in children ($M = 23.8\%, SD = 28.1\%$) than in adults ($M =$
 231 $4.25\%, SD = 8.03\%$), $t(71) = 3.7, p < .001, d = 0.89$ (Figure 2).

232



233

234 **Figure 2: Congruency Effect in children and adults.** IES percentage change between the neutral
235 and incongruent prime items of the non-symbolic numerical comparison task in children and adults.
236 Error bars represent \pm one standard error of the mean.

237

238 *Negative Priming Effects: Analyses of the Probe Items*

239 We conducted 2 age group (children vs. adults) x 2 trial type (test vs. control) repeated
240 measures ANOVA on the probe IES (see Table 2 for descriptive statistics on the probe
241 items).

242

243

244

245

246

247

248

249

250

251 Table 2

252 *Average and range of ARs and RTs (ms) for the congruent test and control probe items of the*
 253 *non-symbolic numerical comparison task.*

	7-8-year-olds		Adults	
	M (SD)	Range	M (SD)	Range
Test probe items				
Ars	0.62 (0.23)	0.14 - 1	0.82 (0.12)	0.55 - 1
RTs	907 (260)	470 - 1871	681 (201)	435 - 1340
Control probe items				
Ars	0.79 (0.13)	0.5 - 1	0.85 (0.13)	0.52 - 1
RTs	819 (228)	412 - 1514	635 (173)	413 - 1224

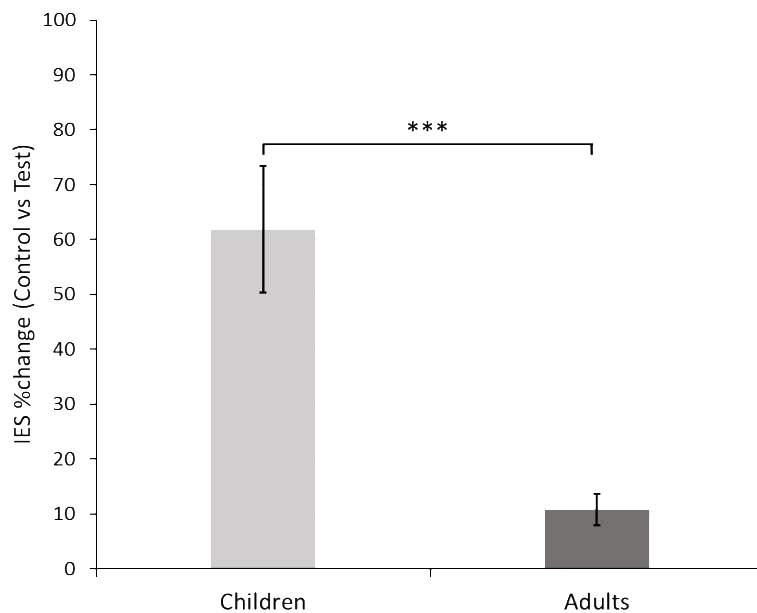
254

255

256 The analysis revealed a significant effect of age group, with adults ($M = 822$, $SD = 535$)
 257 showing overall lower IES than children ($M = 1406$, $SD = 535$), $F(1, 71) = 20.99$, $p < .0001$,
 258 $\eta^2_p = 0.23$. Importantly, we observed a significant main effect of the type of trial (test vs.
 259 control) with a smaller IES in the control ($M = 924$, $SD = 330$) than in the test ($M = 1305$, SD
 260 $= 857$) trials, $F(1, 71) = 21.09$, $p < .0001$, $\eta^2_p = 0.23$. There was a significant interaction
 261 between age group and trial type, $F(1, 71) = 12.45$, $p = .001$, $\eta^2_p = 0.15$.

262 When performing paired t-tests looking at both age groups separately, we observed a
 263 significant negative priming effect on IES for both children (test: $M = 1743$, $SD = 1057$,
 264 control: $M = 1069$, $SD = 355$), $t(42) = 4.91$, $p < .0001$, $d = 1.039$, and adults (test: $M = 867$,
 265 $SD = 352$, control: $M = 778$, $SD = 273$), $t(29) = 3.4$, $p = .002$, $d = 0.748$. . In addition, we
 266 found that the amplitude of the negative priming effect computed as a percent change of IES
 267 between the control and the test trials was larger in children ($M = 61.8\%$, $SD = 75.7\%$) than
 268 in adults ($M = 10.8\%$, $SD = 15.4\%$), $t(71) = 3.63$, $p = .001$, $d = 0.87$ (Figure 3).

269



270

271 **Figure 3: Negative Priming Effect in children and adults.** IES percentage change on the probe
272 between the control and test trials of the non-symbolic numerical comparison task in children and
273 adults. Error bars represent \pm one standard error of the mean.

274

275 Discussion

276 Using a negative priming paradigm, we provided additional evidence for the role of
277 inhibitory control processes in non-symbolic numerical comparison tasks. First, consistent
278 with previous studies (Hurewitz et al., 2006; Szűcs et al., 2013), we observed a congruency
279 effect on the prime items. Both 7-8-year-olds and adults performed significantly worse when
280 comparing two dot arrays in a 1:2 numerical ratio when *Size* was incongruent with
281 numerosity than when *Size* was constant across the two arrays.

282 Second, we observed significant negative priming effects both in 7-8 year-olds and in adults:
283 When comparing two arrays of dots in which numerosity was congruent with *Size*, the
284 performances were lower when the preceding item showed a conflict between number and
285 *Size* than when *Size* was identical in the two arrays of the preceding item. These negative
286 priming effects provide evidence that 7-8-year-olds and adults inhibited *Size* to process
287 numerosity in the incongruent prime items of the non-symbolic numerical comparison task.

288 Hence, our results demonstrate, first, that inhibitory control processes are required to block
289 irrelevant dimensions of magnitude during numerical comparison, impacting both the
290 performance on the current and the following item, in children at the beginning of primary
291 school and even in adults with a precise numerical acuity (adults can accurately perceive the
292 difference between two numerosities in a numerical ratio up to 9:10). Second, we observe
293 that, for a given level of numerical difficulty, the amplitude of the negative priming effect
294 decreases between 7-8-year-olds and adults, supporting the idea that the ability to compare
295 numerosities could be rooted at least in part on the growing ability to inhibit an irrelevant
296 non-numerical dimension of *Size*, in line with a more general protracted development of
297 inhibitory control (Dempster & Corkill, 1999; Harnishfeger & Bjorklund, 1994). This
298 decrease in the amplitude of the negative priming effect is consistent with the one reported in
299 previous developmental negative priming studies including negative priming adaptation of
300 logico-mathematical tasks (Borst, Moutier, & Houdé, 2013; Borst, Poirel, et al., 2012, 2013;
301 Houdé & Guichart, 2001). This is, however, in contrast with other studies having found either
302 no difference in negative priming between children and adults (Pritchard & Neumann, 2009),
303 or smaller if not an absence of negative priming in children compared to adult participants
304 (Tipper et al., 1989). These discrepant findings could be accounted for by the different
305 inhibitory control processes involved in different experimental contexts. For instance,
306 Lechuga and colleagues (2006) have argued that a distinction should be drawn between
307 intentional and automatic inhibitory control. In our study, it is possible that the inhibitory
308 control required to block the irrelevant, non-numerical dimensions of magnitude in the
309 numerical comparison task, is an automated process in adults, but not yet automatized in 7-8-
310 year-olds, consistent with the idea of a development of numerical representation relying on a
311 progressive ability to abstract number from non-numerical dimensions (Piazza, De Feo,
312 Panzeri, & Dehaene, 2018). **In a study investigating the development of negative priming**

313 effects between children, adolescents and adults, Pritchard and Neumann (2009) recommend
314 to correct reaction time data for age-related differences in overall response speed. We did so
315 in the present study by performing our analyses on a percentage change in IES, rather than on
316 absolute difference. Thus, our observed differences in the amplitude of the negative priming
317 effect cannot be accounted for by overall differences in reactions times between children and
318 adults. However, further studies investigating multiple age ranges between the ones reported
319 in the current study need to be conducted in order to fully describe the developmental
320 trajectory of the role played by inhibitory control in non-symbolic numerical comparison
321 judgements.

322 One limit of using negative priming paradigm is its applicability to very young population.
323 First, negative priming effects are usually reported on the basis of analyses of reaction times,
324 which are less easily collectable in preschoolers. Most studies investigating numerical
325 comparison abilities in preschool children report analyses on accuracy levels, rather than
326 reaction times, which are often derived from button presses performed by the experimenters
327 themselves. Second, the logic of the negative priming paradigm requires to restrict the
328 analyses of performance on probe items preceded by correctly performed incongruent prime
329 items. Low accuracy scores on incongruent trials in preschoolers could have precluded the
330 analysis of a negative priming effect in this population. In the current study, we were able to
331 report negative priming effects calculated on the basis of IES in 7-8 year old children and in
332 adults having performed the same numerical comparison task, both in terms of presentation
333 times and numerical ratios.

334

335 One could argue that participants are less efficient to compare numerosities in congruent
336 items preceded by incongruent than neutral ones (i.e., negative priming effect) not because
337 they need to inhibit *Size* in incongruent items but because neutral items are easier to perform

338 than incongruent ones which could in turn affect the level of internal confidence of the
339 participant (Odic et al., 2014). However, these hysteresis effects have been observed after
340 prolonged exposure to difficult trials, and not from one trial to the next, as in our task.
341 Moreover, our participants were not given any feedback on their performance, which has
342 been shown to be crucial to evoke such hysteresis effect during numerical judgment tasks
343 (Odic et al., 2014; Experiment 3). Additionally, negative priming effects have been observed
344 initially in the Color-Word Stroop task (Dalrymple-Alford & Budayer, 1966; Pritchard &
345 Neumann, 2009) in which test and control trials were equivalent in terms of the difficulty of
346 the primes (both items were incongruent), and differed solely by the color to be activated in
347 the following probe items (either identical or different than the color inhibited in the prime).
348 Although the negative priming effects reported in the present study suggest that item size
349 must be inhibited in incongruent items to process numerosities in children and adults, further
350 studies are needed to determine whether (a) other irrelevant dimensions must be inhibited too
351 and (b) whether the amplitude of the negative priming effect would also decrease with age
352 especially for irrelevant dimensions that remain highly salient throughout development.
353 Convex hull might be a good candidate to test this hypothesis given that its impact remains
354 relatively stable throughout development, unlike the impact of item size which decreases with
355 age (Gilmore et al., 2016).

356

357 *Conclusion*

358 Our study reports the first evidence of negative priming effects in numerical estimation tasks
359 in 7-8-year-olds and adults, and thus provides an additional piece of evidence for the role of
360 inhibitory control processes involved in basic numerical intuitions. Together with the
361 observed developmental effect, our findings support the role of executive functions, and in
362 particular of inhibitory control, in numerical development, by using a different

363 methodological approach. This is in line with recent accounts of numerical development
364 (Gebuis et al., 2016, Leibovich et al., 2017), as well as with recent evidence showing that the
365 development of numerical skills relies on the ability to filter irrelevant dimensions of quantity
366 (Piazza et al., 2018).

367 Consistent with these accounts of numerical development, some studies have reported that
368 the association between numerical estimation and math could be explained by inter-
369 individual differences in inhibitory control efficiency (Fuhs & McNeil, 2013; Gilmore et al.,
370 2013; Merkley, Thompson, & Scerif, 2016; but see Keller & Libertus, 2015, for contradictory
371 results). Adapting numerical estimation tasks to a negative priming paradigm such as
372 described in our study allows measuring the ability to inhibit a specific irrelevant dimension
373 of magnitude (i.e. the dimension which is incongruent with numerosity in the prime items).
374 Adapting such method in preschool children (in particular, by ensuring high accuracy levels
375 on the incongruent prime items) could provide an alternative way of measuring children's
376 inhibitory control abilities for specific irrelevant dimensions, allowing to subsequently
377 determine their respective predictive value for the development of more general mathematics
378 skills. Our findings thus have important implications for the current debates regarding the
379 predictive value of numerical intuitions vs. executive functions for math achievement, by
380 providing tentative evidence for the latter.

381

382

383 **References**

- 384 Aïte, A., Berthoz, A., Vidal, J., Roell, M., Zaoui, M., Houdé, O., & Borst, G. (2016). Taking
385 a third-person perspective requires inhibitory control: Evidence from a developmental
386 negative priming study. *Child Development, 87*, 1825-1840
- 387 Arend, I., & Henik, A. (2015). Choosing the larger versus choosing the smaller: Asymmetries
388 in the size congruity effect. *Journal of Experimental Psychology. Learning, Memory, and*
389 *Cognition, 41*(6), 1821–1830. <https://doi.org/10.1037/xlm0000135>
- 390 Borst, G., Moutier, S., & Houdé, O. (2013). Negative priming in logicomathematical
391 reasoning: The cost of blocking your intuition. In W. De Neys & M. Osman (Eds.), *New*
392 *approaches in reasoning research—Current issues in thinking & reasoning* (pp. 54–71). New
393 York: Psychology Press.
- 394 Borst, G., Poirel, N., Pineau, A., Cassotti, M., & Houdé, O. (2013). Inhibitory control
395 efficiency in a Piaget-like class-inclusion task in school-age children and adults: A
396 developmental negative priming study. *Developmental Psychology, 49*, 1366-1374.
- 397 Borst, G., Poirel, N., Pineau, A., Cassotti, M., & Houdé, O. (2012). Inhibitory control in
398 number-conservation and class-inclusion tasks: A neo-Piagetian inter-task priming study.
399 *Cognitive Development, 27*(3), 283–298. <https://doi.org/10.1016/j.cogdev.2012.02.004>
- 400 Cantlon, J. F., Brannon, E. M., Carter, E. J., & Pelphrey, K. A. (2006). Functional Imaging of
401 Numerical Processing in Adults and 4-y-Old Children. *PLoS Biology, 4*(5).
402 <https://doi.org/10.1371/journal.pbio.0040125>
- 403 Cappelletti, M., Didino, D., Stoianov, I., & Zorzi, M. (2014). Number skills are maintained in
404 healthy ageing. *Cognitive Psychology, 69*, 25–45.
405 <https://doi.org/10.1016/j.cogpsych.2013.11.004>

- 406 Clayton, S., & Gilmore, C. (2015). Inhibition in Dot Comparison Tasks. *ZDM: The*
407 *International Journal on Mathematics Education*, 47(5), 759–770.
408 <https://doi.org/10.1007/s11858-014-0655-2>
- 409 Dalrymple-Alford, E. C., & Budayer, B. (1966). Examination of some aspects of the Stroop
410 Color-Word Test. *Perceptual and Motor Skills*, 23(3), 1211–1214.
411 <https://doi.org/10.2466/pms.1966.23.3f.1211>
- 412 Defever, E., Reynvoet, B., & Gebuis, T. (2013). Task- and age-dependent effects of visual
413 stimulus properties on children's explicit numerosity judgments. *Journal of Experimental*
414 *Child Psychology*, 116(2), 216–233. <https://doi.org/10.1016/j.jecp.2013.04.006>
- 415 Dehaene, S. (1997). *The number sense: How the mind creates mathematics*. New York:
416 Oxford University Press.
- 417 Dehaene, S. (2003). The neural basis of the Weber-Fechner law: a logarithmic mental number
418 line. *Trends in Cognitive Sciences*, 7(4), 145–147.
- 419 de Hevia, M. D., Izard, V., Coubart, A., Spelke, E. S., & Streri, A. (2014). Representations of
420 space, time, and number in neonates. *Proceedings of the National Academy of Sciences of the*
421 *United States of America*, 111(13), 4809–4813. <https://doi.org/10.1073/pnas.1323628111>
- 422 de Hevia, M.-D., Girelli, L., Bricolo, E., & Vallar, G. (2008). The representational space of
423 numerical magnitude: illusions of length. *Quarterly Journal of Experimental Psychology*
424 (2006), 61(10), 1496–1514. <https://doi.org/10.1080/17470210701560674>
- 425 Dempster, F. N., & Corkill, A. J. (1999). Interference and Inhibition in Cognition and
426 Behavior: Comments on the Commentaries. *Educational Psychology Review*, 11(2), 129–
427 141. <https://doi.org/10.1023/A:1022024408911>
- 428 DeWind, N. K., Adams, G. K., Platt, M. L., & Brannon, E. M. (2015). Modeling the
429 approximate number system to quantify the contribution of visual stimulus features.
430 *Cognition*, 142, 247–265. <https://doi.org/10.1016/j.cognition.2015.05.016>

- 431 Feigenson, L., Dehaene, S., & Spelke, E. (2004). Core systems of number. *Trends in*
432 *Cognitive Sciences*, 8(7), 307–314. <https://doi.org/10.1016/j.tics.2004.05.002>
- 433 Fuhs, M. W., & McNeil, N. M. (2013). ANS acuity and mathematics ability in preschoolers
434 from low-income homes: contributions of inhibitory control. *Developmental Science*, 16(1),
435 136–148. <https://doi.org/10.1111/desc.12013>
- 436 Fuhs, M. W., McNeil, N. M., Kelley, K., O’Rear, C., & Villano, M. (2016). The Role of Non-
437 Numerical Stimulus Features in Approximate Number System Training in Preschoolers from
438 Low-Income Homes. *Journal of Cognition and Development*, 17(5), 737–764.
439 <https://doi.org/10.1080/15248372.2015.1105228>
- 440 Gabay, S., Leibovich, T., Henik, A., & Gronau, N. (2013). Size before numbers: Conceptual
441 size primes numerical value. *Cognition*, 129(1), 18–23.
442 <https://doi.org/10.1016/j.cognition.2013.06.001>
- 443 Gebuis, T., Cohen Kadosh, R., & Gevers, W. (2016). Sensory-integration system rather than
444 approximate number system underlies numerosity processing: A critical review. *Acta*
445 *Psychologica*, 171, 17–35. <https://doi.org/10.1016/j.actpsy.2016.09.003>
- 446 Gebuis, T., Herfs, I. K., Kenemans, J. L., de Haan, E. H. F., & van der Smagt, M. J. (2009).
447 The development of automated access to symbolic and non-symbolic number knowledge in
448 children: an ERP study. *The European Journal of Neuroscience*, 30(10), 1999–2008.
449 <https://doi.org/10.1111/j.1460-9568.2009.06994.x>
- 450 Gebuis, T., & Reynvoet, B. (2012a). The Role of Visual Information in Numerosity
451 Estimation. *PLOS ONE*, 7(5), e37426. <https://doi.org/10.1371/journal.pone.0037426>
- 452 Gebuis, T., & Reynvoet, B. (2012b). The interplay between nonsymbolic number and its
453 continuous visual properties. *Journal of Experimental Psychology. General*, 141(4), 642–648.
454 <https://doi.org/10.1037/a0026218>

- 455 Gilmore, C., Attridge, N., Clayton, S., Cragg, L., Johnson, S., Marlow, N., ... Inglis, M.
456 (2013). Individual differences in inhibitory control, not non-verbal number acuity, correlate
457 with mathematics achievement. *PloS One*, 8(6), e67374.
458 <https://doi.org/10.1371/journal.pone.0067374>
- 459 Gilmore, C., Cragg, L., Hogan, G., & Inglis, M. (2016). Congruency effects in dot
460 comparison tasks: convex hull is more important than dot area. *Journal of Cognitive*
461 *Psychology (Hove, England)*, 28(8), 923–931.
462 <https://doi.org/10.1080/20445911.2016.1221828>
- 463 Halberda, J., & Feigenson, L. (2008). Developmental change in the acuity of the ‘Number
464 Sense’: The Approximate Number System in 3-, 4-, 5-, and 6-year-olds and adults.
465 *Developmental Psychology*, 44(5), 1457–1465. <https://doi.org/10.1037/a0012682>
- 466 Harnishfeger, K. K., & Bjorklund, D. F. (1994). A developmental perspective on individual
467 differences in inhibition. *Learning and Individual Differences*, 6(3), 331–355.
468 [https://doi.org/10.1016/1041-6080\(94\)90021-3](https://doi.org/10.1016/1041-6080(94)90021-3)
- 469 Henik, A., & Tzelgov, J. (1982). Is three greater than five: The relation between physical and
470 semantic size in comparison tasks. *Memory & Cognition*, 10(4), 389–395.
471 <https://doi.org/10.3758/BF03202431>
- 472 Houdé, O., & Guichart, E. (2001). Negative priming effect after inhibition of number/length
473 interference in a Piaget-like task. *Developmental Science*, 4, 119–123. doi:10.1111/1467-
474 7687.00156
- 475 Hubbard, E. M., Piazza, M., Pinel, P., & Dehaene, S. (2005). Interactions between number
476 and space in parietal cortex. *Nat Rev Neurosci*, 6(6), 435–448.
477 <https://doi.org/10.1038/nrn1684>

- 478 Hurewitz, F., Gelman, R., & Schnitzer, B. (2006). Sometimes area counts more than number.
479 *Proceedings of the National Academy of Sciences*, *103*(51), 19599–19604.
480 <https://doi.org/10.1073/pnas.0609485103>
- 481 Keller, L., & Libertus, M. (2015). Inhibitory control may not explain the link between
482 approximation and math abilities in kindergarteners from middle class families. *Frontiers in*
483 *Psychology*, *6*. <https://doi.org/10.3389/fpsyg.2015.00685>
- 484 Lechuga, M. T., Moreno, V., Pelegrina, S., Gómez-Ariza, C. J., & Bajo, M. T. (2006). Age
485 differences in memory control: evidence from updating and retrieval-practice tasks. *Acta*
486 *Psychologica*, *123*(3), 279–298. <https://doi.org/10.1016/j.actpsy.2006.01.006>
- 487 Leibovich, T., Diesendruck, L., Rubinsten, O., & Henik, A. (2013). The importance of being
488 relevant: modulation of magnitude representations. *Frontiers in Psychology*, *4*.
489 <https://doi.org/10.3389/fpsyg.2013.00369>
- 490 Leibovich, T., Katzin, N., Harel, M., & Henik, A. (2017). From ‘sense of number’ to ‘sense
491 of magnitude’: The role of continuous magnitudes in numerical cognition. *The Behavioral*
492 *and Brain Sciences*, *40*, e164. <https://doi.org/10.1017/S0140525X16000960>
- 493 Luna, B., Padmanabhan, A., & O’Hearn, K. (2010). What has fMRI told us about the
494 development of cognitive control through adolescence? *Brain and Cognition*, *72*(1), 101–
495 113. <https://doi.org/10.1016/j.bandc.2009.08.005>
- 496 Merkley, R., Thompson, J., & Scerif, G. (2016). Of Huge Mice and Tiny Elephants:
497 Exploring the Relationship Between Inhibitory Processes and Preschool Math Skills.
498 *Frontiers in Psychology*, *6*. <https://doi.org/10.3389/fpsyg.2015.01903>
- 499 Neill, W.T., Valdes, L.A., & Terry, K.M. (1995). Selective attention and Inhibitory control of
500 cognition, in *Interference and Inhibition in Cognition*, eds F. N. Dempster and C.J. Brainerd
501 (New York, NY: Academic Press), 207–261. doi: 10.1016/B978-012208930-5/50008-8

- 502 Nys, J., & Content, A. (2012). Judgement of discrete and continuous quantity in adults:
503 number counts! *Quarterly Journal of Experimental Psychology (2006)*, *65*(4), 675–690.
504 <https://doi.org/10.1080/17470218.2011.619661>
- 505 Odic, D., Libertus, M. E., Feigenson, L., & Halberda, J. (2013). Developmental change in the
506 acuity of approximate number and area representations. *Developmental Psychology*, *49*(6),
507 1103–1112. <https://doi.org/10.1037/a0029472>
- 508 Odic, D., Hock, H., & Halberda, J. (2014). Hysteresis affects approximate number
509 discrimination in young children. *Journal of Experimental Psychology. General*, *143*(1),
510 255–265. <https://doi.org/10.1037/a0030825>
- 511 Pavese, A., & Umiltà, C. (1999). Further evidence on the effects of symbolic distance on
512 Stroop-like interference. *Psychological Research*, *62*(1), 62–71.
513 <https://doi.org/10.1007/s004260050040>
- 514 Piaget, J. (1952). *The child's conception of number*. London: Routledge & Kegan Paul, Ltd.
- 515 Piazza, M., Izard, V., Pinel, P., Le Bihan, D., & Dehaene, S. (2004). Tuning curves for
516 approximate numerosity in the human intraparietal sulcus. *Neuron*, *44*(3), 547–555.
517 <https://doi.org/10.1016/j.neuron.2004.10.014>
- 518 Piazza, M., De Feo, V., Panzeri, S., & Dehaene, S. (2018). Learning to focus on number.
519 *Cognition*, *181*, 35–45. <https://doi.org/10.1016/j.cognition.2018.07.011>
- 520 Pinel, P., Piazza, M., Le Bihan, D., & Dehaene, S. (2004). Distributed and overlapping
521 cerebral representations of number, size, and luminance during comparative judgments.
522 *Neuron*, *41*(6), 983–993.
- 523 Pritchard, V. E., & Neumann, E. (2009). Avoiding the potential pitfalls of using negative
524 priming tasks in developmental studies: assessing inhibitory control in children, adolescents,
525 and adults. *Developmental Psychology*, *45*(1), 272–283. <https://doi.org/10.1037/a0014168>

- 526 Rousselle, L., & Noël, M.-P. (2008). The development of automatic numerosity processing in
527 preschoolers: Evidence for numerosity-perceptual interference. *Developmental Psychology*,
528 44(2), 544–560. <https://doi.org/10.1037/0012-1649.44.2.544>
- 529 Rousselle, L., Palmers, E., & Noël, M.-P. (2004). Magnitude comparison in preschoolers:
530 what counts? Influence of perceptual variables. *Journal of Experimental Child Psychology*,
531 87(1), 57–84. <https://doi.org/10.1016/j.jecp.2003.10.005>
- 532 Salti, M., Katzin, N., Katzin, D., Leibovich, T., & Henik, A. (2017). One tamed at a time: A
533 new approach for controlling continuous magnitudes in numerical comparison tasks.
534 *Behavior Research Methods*, 49(3), 1120–1127. <https://doi.org/10.3758/s13428-016-0772-7>
- 535 Schwarz, W., & Ischebeck, A. (2003). On the relative speed account of number-size
536 interference in comparative judgments of numerals. *Journal of Experimental Psychology*.
537 *Human Perception and Performance*, 29(3), 507–522.
- 538 Soltész, F., Szűcs, D., & Szűcs, L. (2010). Relationships between magnitude representation,
539 counting and memory in 4- to 7-year-old children: A developmental study. *Behavioral and*
540 *Brain Functions*, 6(1), 13.
- 541 Szűcs, D., Nobes, A., Devine, A., Gabriel, F. C., & Gebuis, T. (2013). Visual stimulus
542 parameters seriously compromise the measurement of approximate number system acuity and
543 comparative effects between adults and children. *Frontiers in Psychology*, 4.
544 <https://doi.org/10.3389/fpsyg.2013.00444>
- 545 Tipper, S. P. (1985). The negative priming effect: inhibitory priming by ignored objects. *The*
546 *Quarterly Journal of Experimental Psychology. A, Human Experimental Psychology*, 37(4),
547 571–590.
- 548 Tipper, S. P. (2001). Does negative priming reflect inhibitory mechanisms? A review and
549 integration of conflicting views. *The Quarterly Journal of Experimental Psychology Section*
550 *A*, 54(2), 321–343. <https://doi.org/10.1080/713755969>

- 551 Tokita, M., & Ishiguchi, A. (2013). Effects of perceptual variables on numerosity comparison
552 in 5-6-year-olds and adults. *Frontiers in Psychology, 4*, 431.
553 <https://doi.org/10.3389/fpsyg.2013.00431>
- 554 Townsend, J.T., & Ashby, F.G. (1978). Methods of modeling capacity in simple processing
555 systems. In J. Castellan & F. Restle (Eds.), *Cognitive theory. Vol. 3.* (pp. 200-239). Hillsdale,
556 N.J.: Erlbaum.
- 557 Townsend, J.T., & Ashby, F.G. (1983). *Stochastic modeling of elementary psychological*
558 *processes*. Cambridge: Cambridge University Press
- 559 Viarouge, A., & de Hevia, M. D. (2013). The role of numerical magnitude and order in the
560 illusory perception of size and brightness. *Frontiers in Psychology, 4*.
561 <https://doi.org/10.3389/fpsyg.2013.00484>