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► **To cite this version:**

Sandrine Rossi, Julie Vidal, Marie Letang, Olivier Houdé, Grégoire Borst. Adolescents and adults need inhibitory control to compare fractions. *Journal of Numerical Cognition*, 2019, 5 (3), pp.314-336. 10.5964/jnc.v5i3.197 . hal-02923752

HAL Id: hal-02923752

<https://hal.science/hal-02923752v1>

Submitted on 30 May 2024

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Empirical Research

Adolescents and Adults Need Inhibitory Control to Compare Fractions

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Abstract

For children, adolescents and educated adults, comparing fractions with common numerators (e.g., $4/5$ vs. $4/9$) is more challenging than comparing fractions with common denominators (e.g., $3/4$ vs. $6/4$) or fractions with no common components (e.g., $5/7$ vs. $6/2$). Errors are related to the tendency to rely on the “greater the whole number, the greater the fraction” strategy, according to which $4/9$ seems larger than $4/5$ because 9 is larger than 5. We aimed to determine whether the ability of adolescents and educated adults to compare fractions with common numerators was rooted in part in their ability to inhibit the use of this misleading strategy by adapting the negative priming paradigm. We found that participants were slower to compare the magnitude of two fractions with common denominators after they compared the magnitude of two fractions with common numerators than after they decided which of two fractions possessed a denominator larger than the numerator. The negative priming effects reported suggest that inhibitory control is needed at all ages to avoid errors when comparing fractions with common numerators.

Keywords: conceptual development, fraction comparisons, natural number bias, inhibitory control

Journal of Numerical Cognition, 2019, Vol. 5(3), 314–336, <https://doi.org/10.5964/jnc.v5i3.197>

Received: 2018-07-25. Accepted: 2019-02-10. Published (VoR): 2019-12-20.

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Fraction Comparisons

Learning rational numbers, particularly the concept of fractions, is challenging for students (Lortie-Forgues, Tian, & Siegler, 2015). The acquisition of fraction knowledge in education is important because it constitutes part of the core knowledge for algebraic, probabilistic, and proportional reasoning (Siegler & Lortie-Forgues, 2014). Indeed, fraction knowledge is predictive of mathematic achievement (Jordan et al., 2013; Siegler, Thompson, & Schneider, 2011; Torbeyns, Schneider, Xin, & Siegler, 2015). Notably, fractions not only are difficult for children to master but also remain challenging for adults (for a review, see Vamvakoussi, 2015). Adults and children typically use different strategies to compare the magnitudes of fractions as a function of the type of fraction comparison problems with which they are confronted (see, e.g., Fazio, DeWolf, & Siegler, 2016; Schneider & Siegler, 2010; Siegler et al., 2011; Siegler & Pyke, 2013). In addition, adults tend to represent fractions as discrete magnitudes when simpler strategies are not pertinent (Fazio et al., 2016). Taken together, these findings are in line with the overlapping wave theory proposed by Siegler (1996). Thus, difficulties in learning fractions are due to different factors, such as applying whole-number properties to rational numbers or

applying procedures used in fraction addition (or subtraction) to fraction multiplication (or division; Siegler, Fazio, Bailey, & Zhou, 2013; Torbeyns et al., 2015). An illustration is given in fraction comparison problems in which participants consider a fraction as two separate natural numbers rather than one rational number (Stafylidou & Vosniadou, 2004) in a certain context. For instance, when deciding whether $1/7$ is larger than $1/3$, one could erroneously answer that $1/7$ is larger than $1/3$ because 7 is larger than 3 when considering the fractions as two separate natural numbers.

The natural number bias (Vamvakoussi, Van Dooren, & Verschaffel, 2012), defined as a robust human tendency to rely on natural number knowledge when working with rational numbers (Ni & Zhou, 2005) could be in part at the root of systematic errors when comparing fractions with common numerators (e.g., $1/7$ vs. $1/3$). Because the concept of a natural number coexists with the concept of a rational number (Chi, 1992, 2005; diSessa, 2008; diSessa & Sherin, 1998; Posner, Strike, Hewson, & Gertzog, 1982; Vosniadou, 2013; Vosniadou & Skopeliti, 2014; Vosniadou, Vamvakoussi, & Skopeliti, 2008), the concept of a natural number might interfere with the concept of a rational number in certain contexts, resulting in a natural number bias. This bias persists from childhood to adulthood in fraction comparison problems likely because (as with other cognitive biases) it is highly efficient in certain contexts, such as when the two fractions to compare have the same denominator (e.g., $4/6$ vs. $7/6$). In this context, applying natural number knowledge (i.e., that 4 is smaller than 7) when comparing $4/6$ vs. $7/6$, leads to the correct answer that $7/6$ (1.16) is larger than $4/6$ (0.66). However, it is worth noting that previous studies have demonstrated that natural number knowledge is crucial for mathematical achievement (Siegler & Lortie-Forgues, 2014) and for the development of conceptual and procedural knowledge of fractions in particular (e.g., Rinne, Ye, & Jordan, 2017).

Van Dooren, Lehtinen, and Verschaffel (2015) have argued that the systematic difficulty in comparing fractions with common numerators (as revealed by higher error rates or longer response times) at any age might be rooted in part in our spontaneous tendency to rely on a well-known strategy (i.e., the “greater the whole number, the greater the fraction” strategy) in a context in which this strategy is not appropriate. Consistent with this assumption, studies have reported that children (Gabriel, Szucs, & Content, 2013a; Meert, Grégoire, & Noël, 2010a), adolescents (Van Hoof et al., 2013), educated adults (Meert, Grégoire, & Noël, 2009, 2010b; Vamvakoussi, Van Dooren, & Verschaffel, 2012) and experts in mathematics (Obersteiner, Van Dooren, Van Hoof, & Verschaffel, 2013) require more time to compare fractions with common numerators (i.e., a context in which the “greater the number, the greater the fraction” strategy is misleading) than with common denominators (i.e., a context in which the “greater the number, the greater the fraction” strategy is appropriate). While educated adults tend to rely on “the greater the number, the greater the fraction” strategy to compare fractions with common components and thus continue to be affected by the natural number bias (Bonato, Fabbri, Umiltà, & Zorzi, 2007; Meert et al., 2009), they are less affected by it when comparing fractions with different components, presumably because this context might trigger to a lesser extent this misleading strategy (Faulkenberry & Pierce, 2011; Gabriel, Szucs, & Content, 2013b; Schneider & Siegler, 2010; Sprute & Temple, 2011).

According to Alibali and Sidney (2015), several factors could affect the natural number bias observed in fraction comparison tasks such as the strength and preciseness of rational number representations. They speculate that the strength of these rational number representations could be dependent on the participant’s experience with fractions, the delay from the time they last activated this representation and the characteristics of the problem to solve that might trigger one sort of representation over the other. Cognitive development and schooling also affects fraction magnitude abilities as rational and whole number representations become increasingly

more precise over time (see [Siegler et al., 2011](#)). However, the fact that even expert mathematicians display a natural number bias in certain context contradict these findings ([Obersteiner et al., 2013](#)).

Taken together, findings from these previous studies tentatively suggest that participants might be more error prone when comparing two fractions with common numerators because they apply a well-known strategy consisting of choosing the fraction with the greater whole number when the fractions have common components (i.e., the “greater the whole number, the greater the fraction” strategy). While this strategy is efficient for comparing fractions with common denominators, it can lead to systematic errors when comparing fractions with common numerators. In this context, the present study aimed to determine whether the inhibition of the well-known “greater the whole number, the greater the fraction” strategy is needed to compare fractions with common numerators in adolescents and in educated adults as in other types of logico-mathematical problems.

Inhibition of Misleading Strategies During Logico-Mathematical Problem Resolution

According to dual-process theories of human thinking ([Evans, 2008](#); [Evans & Stanovich, 2013](#); [Kahneman, 2011](#)), systematic reasoning errors (or reasoning biases) in different domains are rooted, in part, in our spontaneous tendency to rely on heuristics (i.e., rapid, parallel, automatic, and effortless strategies). Studies have provided convergent evidence that inhibitory control is necessary at any age to avoid using a misleading heuristic in a context in which it interferes with the strategy (or the strategies) leading to the correct answer (see for reviews [Bjorklund & Harnishfeger, 1995](#); [Borst, Aïte, & Houdé, 2015](#); [Diamond, 2013](#); [Houdé & Borst, 2015](#)). For example, studies have demonstrated that the ability to overcome systematic errors in classical developmental tasks such as in Piaget’s A-B ([Diamond, 1998](#) but see [Munakata, 1998](#) for a working memory account of the A-not-B error), class-inclusion ([Borst, Poirel, Pineau, Cassotti, & Houdé, 2013](#); [Perret, Paour, & Blaye, 2003](#)) and number-conservation ([Houdé & Guichart, 2001](#); [Houdé et al., 2011](#)) tasks is not exclusively rooted in the acquisition of knowledge of increasing complexity (as Piaget assumed, [Piaget, 1983](#)) but is also dependent on the progressive ability to inhibit misleading heuristics.

Importantly, the failure to inhibit a misleading strategy partly explains not only systematic errors in logical Piagetian problems but also systematic difficulties faced by children in literacy ([Ahr, Houdé, & Borst, 2016](#); [Borst, Ahr, Roell, & Houdé, 2015](#); [Lanoë, Vidal, Lubin, Houdé, & Borst, 2016](#)), in mathematics ([Lubin et al., 2016](#); [Lubin, Vidal, Lanoë, Houdé, & Borst, 2013](#)) and in science ([Potvin, Masson, Lafortune, & Cyr, 2015](#)).

Some studies have already demonstrated that the inhibition of contextual or perceptual cues is needed to compare fractions. For example, [Siegler and Pyke \(2013\)](#) provided evidence that 6th and 8th graders with better conceptual and procedural knowledge of fractions displayed better performance in an anti-saccade task, a typical inhibitory control task. More generally, comparing the magnitudes of numbers sometimes requires inhibiting contextual or perceptual cues, such as the physical size of the number ([Henik & Tzelgov, 1982](#); [Szűcs & Soltesz, 2007](#)). In addition, switching costs have been reported during arithmetic problem solving (i.e., multiplication of whole numbers), with participants displaying poorer performance when switching between two strategies than when using the same strategy in two consecutive trials ([Lemaire & Lecacheur, 2010](#)). Switching cost has been interpreted as possibly reflecting the role of working memory and/or inhibitory control in strategy choice. However, no study to date has provided evidence that the inhibition of a misleading strategy contributes to the ability to compare fractions with common numerators across development using a negative priming approach.

The Negative Priming Paradigm Adapted to Misleading Strategies

The negative priming paradigm was originally designed by Tipper (1985). The negative priming paradigm rests on the logic that if a distractor (or a strategy) is inhibited on a given item (i.e., the prime), then its activation on the following item (i.e., the probe) should be disrupted (i.e., longer response times and higher error rates) in comparison to a control condition in which the prime does not require inhibition of that strategy (e.g., Borst, Moutier, & Houdé, 2013; Tipper, 2001 but see Neill, Valdes, & Terry, 1995, for a non-inhibitory episodic retrieval account of negative priming). Although neuroimaging studies that investigated the neural underpinning of negative priming used different procedures and different negative priming tasks, there is tentative evidence that the negative priming effect relies on a similar brain area regardless of the nature of the task (see for a review Frings, Schneider, & Fox, 2015). Importantly, negative priming elicits activation in the right dorsolateral prefrontal cortex (Egner & Hirsch, 2005; Krueger, Fischer, Heinecke, & Hagendorf, 2007; Ungar, Nestor, Niznikiewicz, Wible, & Kubicki, 2010) and spatially adjacent regions such as the medial and inferior prefrontal cortex (Wright et al., 2005). These prefrontal areas are closely related to inhibitory control processes (see, e.g., Aron, Robbins, & Poldrack, 2014). Lesions studies provided convergent evidence for the role of the frontal lobe in the negative priming effect, with no negative priming effect observed in patients with frontal lobe lesions (Metzler & Parkin, 2000; Stuss et al., 1999).

Negative priming effects were originally reported in attentional tasks to reveal the inhibition of distractors (e.g., Tipper, Weaver, Cameron, Brehaut, & Bastedo, 1991) but now have been reported in numerous tasks in various domains to reveal the inhibition of overlearned misleading heuristics (see for a review Houdé & Borst, 2015). Note that the negative priming paradigm adapted to misleading strategies reveals that a misleading heuristic must be inhibited in order to solve a given task but provides no information on the strategy that is activated once the misleading heuristic has been inhibited (Borst, Moutier, & Houdé, 2013). In the present study, we used a similar negative priming approach to determine whether the selection of the appropriate strategy to compare fractions with common numerators relies, in part, on the inhibition of a misleading heuristic as previously evidenced in other school learning studies (e.g., Ahr et al., 2016; Borst, Ahr, Roell, & Houdé, 2015; Lanoë et al., 2016; Lubin et al., 2013; Lubin et al., 2016; Potvin et al., 2015). Note that Meert et al. (2009) reported that adults required more time to compare the magnitude of two natural numbers when preceded by fractions with common numerators than when preceded by fractions with common denominators. The authors interpreted this priming effect as an evidence that participants inhibited the selection of the larger denominator when comparing common numerator fractions. Importantly, the priming effect was only observed when the denominators of the common numerator fractions in the prime matched the natural numbers in the probe which does not provide evidence that the “greater the whole number, the greater the fraction” strategy was inhibited. Moreover, it is difficult to determine whether the priming effect reported in this study reflect a positive or a negative priming effect. Indeed, the priming effect could evidence that participants are faster to compare natural numbers when preceded by common denominator fractions in which they can directly compare the components of the fractions to compare their magnitudes.

The Present Study

In the present study, we designed a variant of the negative priming paradigm originally designed by Tipper (1985). Our paradigm was designed in such a way that on test trials, the misleading strategy (i.e., the “greater the whole number, the greater the fraction” strategy) that participants were required to resist (i.e., inhibit) to

solve the prime item became an appropriate strategy for the probe item. Conversely, in control trials, the strategy necessary to complete the prime item was unrelated to the strategy required to solve the probe item. For instance, in the test trial, participants had to determine on the prime which of the two fractions with the same numerator (e.g., $7/4$ vs. $7/3$, hereafter referred as common numerator items) was the largest. This item typically required participants to resist (inhibit) using the “greater the whole number, the greater the fraction” strategy (which would lead participants to erroneously state that $7/4 > 7/3$ because $4 > 3$). After the prime, participants had to determine on the probe which of the two fractions with the same denominator (e.g., $8/3$ vs. $5/3$, hereafter referred as common denominator items) was the largest, a context in which the “greater the whole number, the greater the fraction” strategy was appropriate ($8/3 > 5/3$ because $8 > 3$). In the control trial, participants first decided (on the prime) which of the two fractions ($4/3$ vs. $4/5$, hereafter referred as common-denominator items) had a denominator larger than the numerator (here $4/5$). Then, on the probe, as in the test trial, they determined which of the two fractions with the same denominator ($2/6$ vs. $5/6$) was the largest, a context in which the “greater the whole number, the greater the fraction” strategy was appropriate ($2/6 < 5/6$ because $2 < 5$). Regarding the appropriateness of the method, we note that by construction, the negative priming paradigm requires that the participants succeed above the chance level of performance on the control and test primes for the priming effects on the probes to be observed. Thus, we tested 9th graders who are able to successfully compare the magnitude of common numerator items (i.e., the prime in the test condition in our negative priming paradigm). We also tested young adults because we used age as a proxy of the skill to compare fractions, young adults being more skilled than 9th graders.

We reasoned that if adolescents and educated adults must inhibit the “greater the whole number, the greater the fraction” strategy to compare fractions with common numerators, then they should require more time (and/or commit more errors) when comparing fractions with the same denominator that are preceded by primes when the participants compared fractions with the same numerator than they did when preceded by primes in which participants decided which of the two fractions had a denominator larger than the numerator (revealing a typical negative priming effect). Notably, testing adolescents and adults allowed us to determine (a) whether educated adults must still inhibit the “greater the whole number, the greater the fraction” strategy when comparing common numerator items and (b) whether the efficiency of inhibiting the “greater the whole number, the greater the fraction” strategy in that context increases with age. If inhibitory control is required to compare common numerator items even in educated adults, then we should find negative priming effects in adults. Finally, if the efficiency in inhibiting the misleading heuristic (i.e., the “greater the whole number, the greater the fraction” strategy) increases with age, then the amplitude of the negative priming effect should be smaller in adults than in adolescents, as reported in previous negative priming studies on misleading strategies (e.g., Aïte et al., 2016; Borst, Moutier, & Houdé, 2013; Lanoë et al., 2016).

Method

Participants

Thirty-six typically developing adolescents (mean age \pm SD: 14.6 ± 0.4 years, 17 girls) were recruited from middle schools in Caen (Calvados, France). All of the adolescents were in Grade 9 and had not repeated a year. Thirty-three adults (21 ± 1.7 years, 17 women) without cognitive impairment participated in the study. They were all students from a state university with no selection of the students. Among the 30 adults, 9 were enrolled

in a BA in science and 21 in a BA in humanities and social sciences (4 in law, 6 in history, 4 in sociology and 7 in psychology). The two groups differed significantly in age, $t(67) = 21.4$, $p < .0001$, Cohen's $d = 4.91$, but not in sex repartition, $\chi^2(1) = 0.38$, $p = .53$.

By definition, negative priming effects can be observed only if participants accurately compared common numerator items (i.e., the prime in the test condition). Therefore, 15 adolescents (41% of the sample, $M = 72.3 \pm 19.2\%$ of errors in common numerator items) and 2 adults (6%, $M = 63.4 \pm 4.8$ of errors in common numerator items) were excluded from the analysis because they performed at chance levels of performance. Moreover, we excluded one adolescent and one adult because their average RT exceeded the average RT of the group by more than 3 SD. Thus, analyses were conducted on 20 adolescents (mean age: 14.6 ± 0.3 years, 9 girls, $M = 16.3 \pm 13.5\%$ of errors in common numerator items) and 30 adults (mean age: 21 ± 1.8 years, 14 women, $M = 16 \pm 16.2\%$ of errors in common numerator items). The gender distribution did not differ between the two groups, $\chi^2(1) = 0.01$, $p = .90$.

Written consent was obtained after a detailed discussion and explanations were given. Parental written consent was obtained for the adolescents, who were tested in accordance with national and international norms that govern the use of human research participants. All participants reported normal or corrected-to-normal vision and were native French speakers. All adolescents attended the same middle-school, and all adults attended the same university in Caen, France, serving a diverse population with a wide range of socioeconomic statuses and cultural backgrounds.

Materials

Each item consisted of a visual presentation of two fractions on a computer screen (in 50-point black Arial font on a white background). Between the two fractions, a question mark was displayed. We designed three types of items: common denominator items, common numerator items and denominator-numerator items. In the common denominator items (e.g., $2/4$ vs. $5/4$) and common numerator items (e.g., $4/2$ vs. $4/5$), participants were asked to determine which of the two fractions was the largest. Importantly, participants could rely on the “greater the whole number, the greater the fraction” strategy to determine which of the two fractions was the largest for the fractions with common denominator items, whereas they could not use it for the common numerator items. In the denominator-numerator items, we asked participants to determine which of the two fractions possessed a denominator larger than the numerator. Critically, the inhibition of the “greater the whole number, the greater the fraction” strategy was not needed to solve the denominator-numerator items. Note that the two fractions presented in the denominator-numerator items had the same numerator (e.g., $4/2$ vs. $4/5$) as the common numerator items because the two types of item served as primes in the control and test trials of our negative priming paradigm, respectively. We designed fractions in each item using numbers between 2 and 9 for numerators and denominators (see [Appendix - Fraction design](#)). We presented 24 items (eight of each type) for the practice trials and 96 (32 common denominator items, 16 common numerator items, and 16 denominator-numerator items) for the experimental trials.

Procedure

We tested participants individually in a quiet room on a laptop with a screen resolution of 1366 x 768 pixels. Stimuli were presented using E-prime 2.0 (Psychological Software Tools, Inc., Pittsburgh, USA). Participants started by completing 24 practice trials (8 for each type of item) to familiarize themselves with the three types of

items and the response pad. Feedback was provided regarding whether their answers were correct. To prevent familiarizing participants with the prime-probe sequences, the three types of items were presented in blocks, starting with the common denominator items and finishing with the common numerator items. Next, participants performed 32 experimental trials (16 test and 16 control trials) consisting of pairs of primes and probes during which no feedback was given on the correctness of the responses. In the test trials, participants performed a common numerator item (as a prime) and then a common denominator item (as a probe). In the control trials, participants performed a denominator-numerator item (as a prime) followed by a fraction with a common denominator item (as a probe; see Figure 1). Trials were presented in a random order, with the exception that no more than two test or control trials could occur successively. Each trial started with the presentation of a fixation point followed by a presentation of the type of comparison participants needed to perform on the next item. The question was displayed at the top of the screen in blue and red 24-pt Arial font for half the participants and red and blue font for the other participants, respectively. Then, two fractions were displayed with a question mark in between the two until participants provided an answer. Participants pressed the left (or right) button of the mouse to indicate that the fraction on the left (or the right) of the question mark was the larger one (or had a denominator larger than the numerator). Response times (RTs) were recorded from the onset of the fractions to the button press. Immediately after participants pressed one of the two response buttons, a fixation cross appeared, followed by a presentation of the type of comparison to perform on the next trial. Finally, two fractions and a question mark were displayed until a response was provided. In between each trial, a 450 x 450 pixel blurred jpeg image was displayed in the center of the screen to limit the transfer of processes from one trial to the next. No judgment was required on these images.

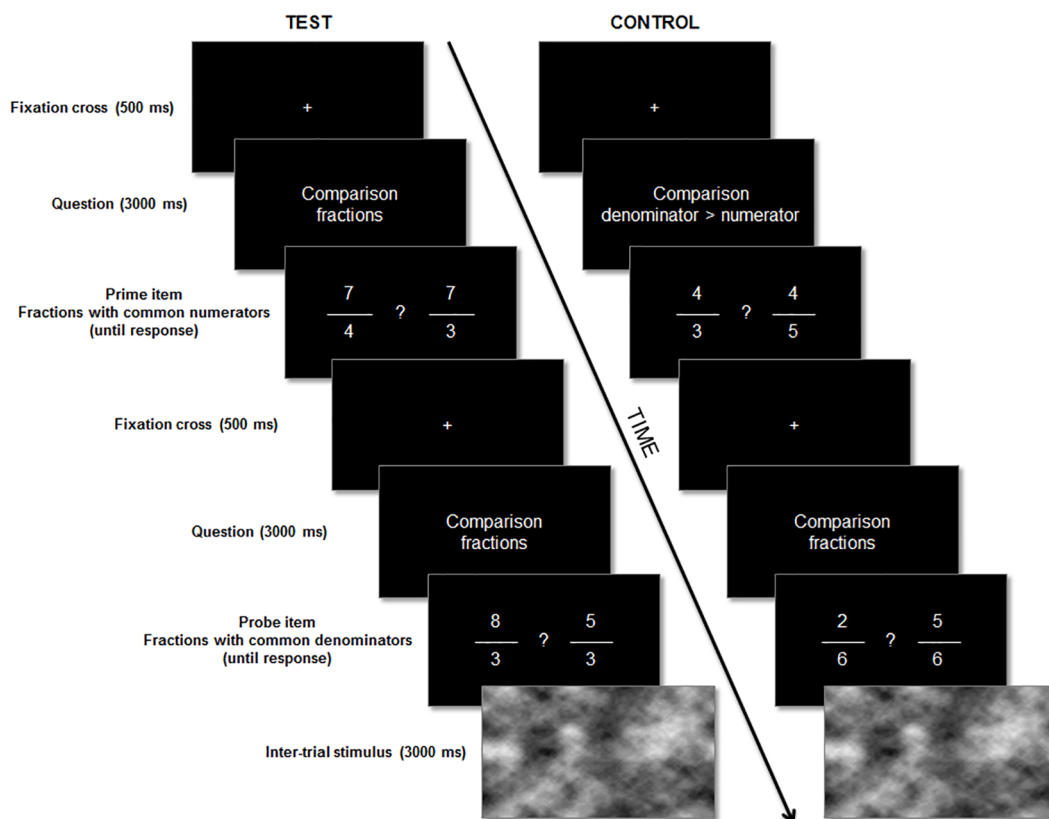


Figure 1. Experimental design. Participant responds by pressing the left or the right button to indicate her or his fraction choice. Items were presented in French.

Given that we were interested in potential priming effects, we standardized the sequence of responses between the primes and the probes in both the test and control trials. The four possible pairs of response sequences occurred two times in both the test and control trials (i.e., ‘left’ on the prime problem then ‘left’ on the probe problem, ‘left’ then ‘right’, ‘right’ then ‘left’, and ‘right’ then ‘right’). Note that participants needed to switch from one strategy to another between the prime and probe items in both types of trials; thus, any difference in probes’ RTs between the control and test trials does not simply reflect switching costs as the ones reported in Lemaire and Lecacheur (2010)’s study.

Results

All analyses of RTs included only data from trials in which participants responded correctly on the prime and the probe. Outliers were defined as RTs greater than 2 SDs from the mean for such participants on the probe items (or the prime items) in the test (or the control) trials. Outliers occurred on 6.7% of trials in adolescents and 6.8% of trials in adults. After removing outliers, participants’ errors and RTs were averaged separately for the prime and probe items on the test and control trials (see Table 1).

Table 1

Means and Standard Deviations (in Parentheses) of ERs (%) and RTs (ms) in Adolescents and Adults

Item	Trial	M (SD)			
		Adolescents		Adults	
		Included (n = 20)	Excluded (n = 14)	Included (n = 30)	Excluded (n = 2)
ERs (%)					
Prime	Test	16.3 (13.5)	72.3 (19.2)	16 (16.2)	63.4 (4.8)
Prime	Control	12.5 (10.1)	15.6 (22.9)	6.4 (9.9)	3 (4.2)
Probe	Test	9.7 (8.2)	27.7 (22.1)	7.9 (11.5)	12.5 (17.7)
Probe	Control	12.2 (12.9)	28.1 (23.7)	8.7 (11.8)	31.3 (8.8)
RTs (ms)					
Prime	Test	3080 (960)		2612 (1082)	
Prime	Control	1751 (693)		1288 (487)	
Probe	Test	2729 (863)		2420 (1010)	
Probe	Control	2538 (859)		2287 (960)	
Negative Priming		192 (392)		134 (426)	

Note. See Appendix for the comparison of included and excluded adolescent ERs and RTs.

When computing the error rates (ERs) on the probe, we included only data from trials in which participants responded correctly on the prime. We conducted separate 2 (type of trials: test or control) x 2 (age: adolescents or adults) analyses of variance (ANOVAs) of the ERs and the RTs for the prime and probe items. For each of the analyses, we report the effect size either in the ANOVA (partial eta squared) or in terms of the difference of the means (Cohen’s *d*). When testing the absence of an interaction effect (which were the effects of interest in our study), Bayesian statistics were used to provide an estimate of the evidence in favor of the null (BF_{01}) or the alternative (BF_{01}) hypothesis. The Bayes factor indexes the extent to which observed data are supported by one model over another. For example, a Bayes Factor (BF_{01}) of 3 in favor of the null hypothesis means that the observed data are 3 times more likely to have occurred under the null than the alternative hypothesis (Jeffreys,

1961). We also provided for the critical interaction hypotheses on the probe items an interpretation of the Bayes Factor according to [Jeffreys \(1961\)](#)'s cutoffs. Bayesian Analyses were performed using the JASP software (Version 0.8.3.1) with a default Cauchy prior width of $r = 0.707$. Note that BFs reported for the interaction reflect the BF of the full interaction model over the main effects model only. Note that because the distributions of the ERs were not normal (all $ps < .01$) but the assumptions of homoscedasticity were confirmed (all $ps > .30$), we ran non-parametric ANOVAs when analyzing ERs on the primes and on the probes.

Primes Analyses

Non parametric one-way (Kruskal-Wallis) and repeated measure (Friedman) ANOVAs on the prime ERs revealed a main effect of the condition, $\chi^2(1) = 6.74$, $p < .01$, $BF_{10} = 19.86$, but no effect of age, $\chi^2(1) = 1.07$, $p = .30$, $BF_{01} = 2.44$, and no two-way interaction, $\chi^2(1) < 1$, $BF_{01} = 0.17$. Adults and adolescents committed more errors when comparing fractions with common numerators (test trials: $16.2 \pm 2.1\%$) than when deciding which fraction had a denominator larger than the numerator (control trials: $9.5 \pm 1.2\%$).

A two-way mixed design ANOVA of the RTs revealed a main effect of the type of trial, $F(1, 48) = 112.35$, $p < .0001$, $\eta_p^2 = .70$, $BF_{10} = 5.36 \times 10^{12}$ - with participants requiring more time to perform common numerator items ($M = 2846 \pm 150$ ms) than denominator-numerator items ($M = 1519 \pm 83$ ms), and a main effect of age, $F(1, 48) = 5.05$, $p = .03$, $\eta_p^2 = .09$, $BF_{10} = 1.16$ - with adults ($M = 1950 \pm 131$ ms) faster than adolescents ($M = 2415 \pm 161$ ms) - but no two-way interactions, $F < 1$, $BF_{01} = 21.71$. Analyses on the type of strategy used by the participants to solve common numerator items and the effect of improper fractions on this comparison can be found in the [Appendix](#).

To determine whether participants required more time to compare two fractions in which one of the two was an improper fraction in common numerator items and whether age modulated this effect, we performed two additional ANOVAs on the prime RTs and ERs of the test trials. A two-way ANOVA of the RTs revealed that participants required less time to solve common numerator items in which one of the two fractions was an improper fraction ($M = 2942 \pm 1151$ ms) than to solve common numerator items in which both fractions were improper or both fractions were not improper ($M = 2673 \pm 916$ ms), $F(1, 48) = 8.62$, $p = .005$, $\eta_p^2 = 0.15$, $BF_{10} = 11.24$, but no effect of age, $F < 1$, $BF_{01} = 2.23$, and no interaction between age and the type of fraction, $F < 1$, $BF_{01} = 5.84$, were observed. A similar ANOVA of the ERs revealed no effect of the type of fraction, $\chi^2(1) < 1$, $BF_{01} = 1.53$, of age, $\chi^2(1) < 1$, $BF_{01} = 2.25$ and of interaction between age and the type of fraction, $\chi^2(1) < 1$, $BF_{01} = 5.04$ for the interaction.

Probes Analyses

Non parametric one-way (Kruskal-Wallis) and repeated measure (Friedman) ANOVAs on the probe ERs revealed no effect of the condition, $\chi^2(1) < 1$, $BF_{01} = 2.81$, no effect of age, $\chi^2(1) = 1.41$, $p = .24$, $BF_{01} = 1.97$, and no two-way interaction, $\chi^2(1) < 1$, $BF_{01} = 11.46$, suggesting a strong evidence in favor of the null hypothesis (i.e., the observed data are more than 11 times more likely to have occurred under the null than the alternative hypothesis). Given that we found no main effect of the type of trials on the ERs, any negative priming effect reported on RTs is unlikely to be due to speed/accuracy trade-offs.

A similar ANOVA on the RTs revealed a main effect of the type of trial, $F(1, 48) = 7.46$, $p < .01$, $\eta_p^2 = .13$, $BF_{10} = 4.25$, but no effect of age, $F(1, 48) = 1.12$, $p = .29$, $BF_{01} = 1.48$, and no two-way interaction, $F < 1$, $BF_{01} = 3.20$.

Note that the Bayes Factor of the interaction suggests moderate evidence in favor of the null hypothesis (i.e., it is about 3 times more likely that there is no difference than a difference in the amplitude of the negative priming effects between adolescents and adults). Importantly, we found that adolescents and adults required more time to perform common denominator items preceded by common numerator items (test trials: $M = 2730 \pm 863$ ms for adolescents and 2421 ± 1010 ms for adults) than those preceded by a denominator-numerator item (2538 ± 859 ms for adolescents and $M = 2287 \pm 960$ ms for adults): $t(19) = 2.08$, $p < .025$, Cohen's $d = 1.07$ for adolescents and $t(29) = 1.77$, $p < .05$, Cohen's $d = 0.73$ for adults (see [Appendix](#) for the effect of improper fractions on the negative priming effects reported).

Primes Versus Probes Analyses

Finally, to verify whether adults and adolescents had more difficulty with common numerator items than with fractions with common denominator items, we conducted a 2 (type of fraction: common numerators vs. common denominators) \times 2 (age: adolescents vs. adults) mixed-design ANOVA on ERs and RTs. To conduct this analysis, we included ERs and RTs for primes in the test trials (i.e., common numerator items) and for probes in the control trials (i.e., common denominator items). Note that we did not include ERs or RTs for probes in the test trials because performance was potentially affected by the prime. Participants required more time in determining which of the two fractions was largest when the two fractions had the same numerator (i.e., primes in the test trials) than when the two fractions had the same denominator (i.e., probes in the control trials), $F(1, 48) = 31.11$, $p < .0001$, $\eta_p^2 = .39$, $BF_{10} = 5621.25$ but we found no main effect of age, $F(1, 48) = 1.74$, $p = .19$, $BF_{01} = 1.32$, and no significant interaction between the type of fraction and age, $F(1, 48) = 1.96$, $p = .17$, $BF_{01} = 1.88$. Non parametric ANOVAs on the ERs revealed a main of type of trials, $\chi^2(1) = 7.53$, $p = .006$, $BF_{10} = 3.69$, but no main effect of age, $\chi^2(1) < 1$, $BF_{01} = 3.28$, and no two-way interaction, $\chi^2(1) < 1$, $BF_{01} = 3.02$.

Discussion

In the present study, we investigated (a) whether inhibitory control is required to compare common numerator items in adolescents and educated adults and (b) whether the efficiency to inhibit the misleading heuristic (i.e., the “greater the whole number, the greater the fraction” strategy) that leads participants to be biased when comparing common numerator items (i.e., the natural number bias) increases between adolescents and adults. In line with previous studies on adolescents ([Van Hoof, Lijnen, Verschaffel, & Van Dooren, 2013](#)) and educated adults ([Meert et al., 2009](#); [Vamvakoussi et al., 2012](#)), we found that adolescents and adults required more time and were less accurate in comparing common numerator items than common denominator items, with adults being generally more efficient than adolescents. We suspect that formal instruction and familiarity with rational numbers might be the cause of the difference observed between adolescents and adults in the present study. One could argue that adults and adolescents might be slower at performing common denominator than common numerator items because they are more familiar with the former than the latter. Although this might be a possibility when rational numbers are first introduced in the mathematical curricula in 4th grade, by Grade 9 and later, students are most likely equally familiar with both types of problems. Thus, we suspect that the difficulty to compare common numerator items in adolescents and adults might be related in part to their tendency to rely on the “greater the whole number, the greater the fraction” strategy whenever fractions possess common numerators, even in a context in which this strategy is misleading such as with fractions with common numerators.

The present study offers an opportunity to go a step further in explaining which process might allow an individual to overcome errors when comparing fractions with common numerators. Indeed, we found that adolescents and adults required more time to compare common denominator items after they had just succeeded in determining which of the two fractions with common numerators was larger than after they succeeded in determining which of the two fractions had a denominator larger than the numerator. Taken together, our results suggest that adolescents and educated adults must inhibit the “greater the whole number, the greater the fraction” strategy when comparing common numerator items. Although the ability to inhibit the “greater the whole number, the greater the fraction” heuristic might contribute to the ability to compare fractions with common numerators, inhibiting contextual or perceptual cues, such as the physical size or the location of the number (see, e.g., Szűcs & Soltesz, 2007), might also be important to compare such fractions.

One could wonder why we did not include a classical inhibitory control task in the present study to show that inhibitory control was involved to solve common numerator items, as in previous studies (see, e.g., Siegler & Pyke, 2013). A limitation of such a correlational approach is that none of the classical inhibitory control tasks assess individual differences in the ability to inhibit a misleading strategy. Thus, the lack of correlation between performance in a classical inhibitory control task and a fraction comparison task does not necessarily reflect that inhibition plays no role in the choice of strategy used to solve the fraction comparison task. On the other hand, the negative priming paradigm has been widely used to demonstrate that inhibitory control is required within a given task to overcome misleading heuristics, and a growing number of studies have successfully applied this paradigm to demonstrate the role of inhibitory control over misleading heuristics in various domains including various school learnings (see, e.g., Aïte et al., 2016; Ahr et al., 2016; Lubin et al., 2013; Lubin et al., 2016; Borst, Moutier, & Houdé, 2013). In addition, the negative priming approach alleviates some of the shortcomings of pure correlational approaches (e.g., lack of causal evidence, directionality of the association reported).

By comparing the performance of adolescents and adults on a negative priming paradigm adapted to fraction comparison, our findings shed light on the development of fraction comparison skills by showing that inhibitory control is needed at all ages to avoid errors when comparing fractions with common numerators. Previous studies have argued that the amplitude of negative priming effects might reflect the ability to inhibit a specific heuristic in a given context (Houdé & Borst, 2014, 2015). Indeed, studies have reported that the amplitude of negative priming effects decreases with age between childhood and adulthood, such as in a verb-inflection task (Lanoë et al., 2016), in a revised version of Piaget’s class-inclusion task (Borst, Poirel, Pineau, Cassotti, & Houdé, 2013) or in a spatial perspective-taking task (Aïte et al., 2016), which has been interpreted as reflecting the increasing ability to inhibit a specific misleading heuristic in each of these domains.

In contrast with these findings, the amplitude of the negative priming effects in our study did not differ between adolescents and adults, which might suggest that the inhibition of a componential processing strategy might be already largely efficient in ninth graders. This finding is consistent with the fact that we did not find that knowledgeable adolescents were less efficient than adults at comparing common numerator items. Note that other studies have also reported no difference in the amplitude of negative priming effects with age (Lubin et al., 2013; Pritchard & Neumann, 2009). A possible explanation as to why some studies but not others reported a difference in the amplitude of the negative priming effects with age might be due to the type of inhibitory control needed in different contexts. Indeed, some authors argue that we should draw a distinction between intentional inhibitory control and automatic inhibitory control (Lechuga, Moreno, Pelegrina, Gómez-Ariza, & Bajo, 2006).

According to this view, whereas intentional inhibitory control is an executive function mediated by the prefrontal cortex (Aron, 2007), automatic inhibitory control relies on automatic processes sustained by brain structures that mature earlier (Lechuga et al., 2006), which would explain the lack of a difference in the negative priming amplitude with age in some contexts. This automatic inhibitory control could potentially appear following intense training (Jasinska, 2013). Indeed, much as one can automatize the activation of a strategy after an intense training, one can potentially automatize the inhibition of a strategy. We argue that the inhibition process (to resist the “greater the whole number, the greater the fraction” strategy) involved in the comparison of fractions with common numerators might be automatized in some students as early as ninth grade, presumably due to intensive schooling on fractions.

We note that using the “greater the whole number, the greater the fraction” strategy to compare fractions with common elements might be a byproduct of the mathematics curricula used in primary school. Indeed, in primary school, simple fractions are first introduced as tools for solving problems that cannot be solved by relying on whole numbers, such as when children need to understand that the “whole” can be divided into n equal parts (e.g., a pizza can be divided in 6 equal parts, each of them representing $1/6$ of the pizza). Thus, children start by manipulating and comparing fractions with common denominators before fractions with common numerators or with no common components. Starting the curricula with the manipulation of fractions with common denominators, a context in which the “greater the whole number, the greater the fraction” strategy is an efficient strategy, might promote the implicit transfer of the properties of whole numbers to fractions. This might explain why inhibition of the “greater the whole number, the greater the fraction” strategy is available at all ages to compare fractions with common numerators. Our finding complements other findings reported in literacy (Ahr et al., 2016; Borst, Ahr, Roell, & Houdé, 2015; Lanoë et al., 2016), mathematics (Lubin et al., 2016; Lubin et al., 2013) and science (Potvin et al., 2015) and provides additional evidence that inhibition might be a core mechanism of learning at school (for reviews see Houdé & Borst, 2015).

The lack of difference in the amplitude of the negative priming effects should be taken with caution given that it can be generalized only to adolescents who succeeded in inhibiting the “greater the whole number, the greater the fraction” strategy when comparing common numerator items. The comparison of adolescents included and excluded from the final sample revealed that excluded adolescents had greater difficulty than included ones solving common numerator and common denominator items. Thus, excluded adolescents might have a lower understanding of fractions in general. That said, we note that they displayed above-chance levels of performance only when performing common denominator items, which suggested that they might be more prone to use the “greater the whole number, the greater the fraction” misleading strategy in this specific context (see Appendix for the details of the analyses).

Our findings suggest that difficulty in inhibiting the “greater the whole number, the greater the fraction” heuristic might contribute to the difficulty comparing fractions with common numerators, but other factors also contribute to such difficulty. Indeed, a number of studies have provided evidence that a lack of conceptual and procedural knowledge on fractions contributes to the specific difficulties in comparing common numerator fractions (e.g., Fazio et al., 2016; Schneider & Siegler, 2010; Siegler et al., 2011; Siegler & Pyke, 2013). Children’s difficulties with fractions have motivated interventions to improve fraction knowledge (Fujimura, 2001; Gabriel et al., 2012; Moss & Case, 1999). The challenge for fraction instruction is to help children understand that magnitudes are a property of not only whole numbers but all real numbers (Siegler et al., 2011). In line with previous studies showing that pedagogical interventions based on inhibitory control learning are more efficient at overcoming

systematic errors in logical reasoning (Houdé et al., 2001; Rossi et al., 2015) or in mathematical reasoning (Rossi, Lubin, Lanoë, & Pineau, 2012; Lubin, Lanoë, Pineau, & Rossi, 2012) than more traditional pedagogical interventions, we suspect that students' understanding of fraction can be improved by using pedagogical interventions based in part on learning to inhibit the "greater the whole number, the greater the fraction" heuristic when comparing fractions with common numerators.

A potential limitation of the present study is that participants were asked to perform a different task on the prime items in the control trial (i.e., determine which of the two fractions has a denominator larger than its numerator) than for all other items (i.e., determine which of the two fractions is the largest). We asked participants to perform a task of a different nature on the prime in the control trial to prevent the strategy being used in the prime items priming the strategy to use on the probe items. However, one could argue that the switching costs between the prime and the probe might differ between the test and the control trials. If so, the negative priming effect could be a consequence of the difference between the switching costs induced by switching between two strategies while performing the same tasks (i.e., comparing the magnitude of fractions) in the test trials and the ones induced by switching between two tasks (i.e., deciding which of the two fractions has a denominator larger than its numerator or which of the two fractions is the largest) in the control trials. However, previous studies reported either no difference in switching costs when switching within the same task or between two tasks (e.g., Allport, Styles, & Hsieh, 1994) or greater switching costs when switching between two tasks than within the same tasks (e.g., Philipp, Kalinich, Koch, & Schubotz, 2008). Thus, it is unlikely that the negative priming effect reported in the present study is a byproduct of the difference in switching costs between the control and test trials.

In addition, one could argue that providing feedbacks during the practice trials could constitute a minimal form of education to the participants and thus change their spontaneous choice of strategy. That said, we note that even if feedback was provided in the practice trials, 41% of adolescents and 6% of adults were excluded because they performed at chance in the negative priming paradigm. Thus, the comparison of fractions with common numerators remains challenging even after receiving feedbacks, which is consistent with the difficulties faced by students at school in this academic learning.

Moreover, the use of single digit numerators and denominators in the common denominator and common numerator items might have encouraged participants to rely more systematically on the "greater the whole number, the greater the fraction" heuristic. Indeed, previous studies demonstrated that the use of a holistic processing strategy increases when fraction comparison tasks include fractions with two digits components and a wider range of numbers (see, e.g., Schneider & Siegler, 2010).

The sample size constitutes another clear limitation of the present study. Indeed, the sample size might be too small to detect a significant age effect on the amplitude of the negative priming effect. Thus, the lack of difference in the amplitude should be interpreted with caution despite the fact that the sample size (after exclusion of participants) was determined pre-hoc on the basis of previous negative priming studies that used similar sample sizes and reported significant effects of age on the amplitude of the negative priming effect (Borst, Moutier, & Houdé, 2013; Lanoë et al., 2016). Note that the Bayes statistics on the interaction effects on the probe responses times and error rates do not entirely alleviate the sample size issue given that they only showed that evidence for the null hypothesis was moderate (i.e., three time more likely to occur than the alternative hypothesis).

In light of these potential limitations, future studies are needed to investigate whether similar negative priming effects can be observed (a) when different prime items are designed in the control trials (b) when no feedbacks are provided in the practice trials, and (c) when a wider range of numbers including two digits number is used to generate the fractions and whether these negative priming effects would vary with age on a larger sample size. Moreover, we need to better understand the role of improper fractions on the emergence of the negative priming effects in the context of fraction comparison (See [Appendix](#) for the analyses of the effect of the improper fractions).

Finally, the degree to which our findings can be generalized to the general population must be considered, given that the participants performed no standardized math test. We note that our sample of adolescents and adults might be representative of their respective parent populations because adolescents were all in Grade 9 in a middle school serving a diverse population (with none of them repeating a year), and adults were undergraduates in a public university serving a diverse population who all obtained a high-school diploma before attending the university.

In conclusion, our study provides the first evidence that inhibitory control is needed in adolescents and educated adults in order to compare fractions with common numerators, as revealed by a negative priming paradigm consistent with studies showing that fraction knowledge is associated with executive functions ([Jordan et al., 2013](#); [Namkung & Fuchs, 2016](#); [Siegler et al., 2012](#)). In addition, our findings provide converging evidence that inhibitory control might be one of the core mechanisms of cognitive development and school learning (for a review, see [Houdé & Borst, 2015](#)).

Competing Interests

The authors have declared that no competing interests exist.

Funding

The authors have no funding to report.

Acknowledgments

We wish to thank Lucie Besnehard and Thomas Augier for their valuable help with the data collection and Margot Roëll for the English editing of the manuscript. We also would like to thank the middle schools and the teachers, the children and their parents for participating.

Ethics Approval

The research procedure was consistent with the principles of the research ethics published by the American Psychological Association.

Data Availability

For this study a dataset is freely available (see the [Supplementary Materials section](#)).

Supplementary Materials

The raw data for the present paper are available via the OSF project page (for access see Index of [Supplementary Materials](#) below).

Index of Supplementary Materials

Rossi, S., Vidal, J., Letang, M., Houdé, O., & Borst, G. (2019). *Supplementary materials to "Adolescents and adults need inhibitory control to compare fractions"* [Research data]. OSF. <https://osf.io/h3a7f/>

References

- Ahr, E., Houdé, O., & Borst, G. (2016). Inhibition of the mirror generalization process in reading in school-aged children. *Journal of Experimental Child Psychology*, *145*, 157-165. <https://doi.org/10.1016/j.jecp.2015.12.009>
- Aïte, A., Berthoz, A., Vidal, J., Roell, M., Zaoui, M., Houdé, O., & Borst, G. (2016). Taking a third-person perspective requires inhibitory control: Evidence from a developmental negative priming study. *Child Development*, *87*, 1825-1840. <https://doi.org/10.1111/cdev.12558>
- Alibali, M. W., & Sidney, P. J. (2015). Variability in the natural number bias: Who, when, how, and why. *Learning and Instruction*, *37*, 56-61. <https://doi.org/10.1016/j.learninstruc.2015.01.003>
- Allport, A., Styles, E. A., & Hsieh, S. (1994). Shifting intentional set: Exploring the dynamic control of tasks. In C. Umiltà & M. Moscovitch (Eds.), *Attention and Performance XV: Conscious and nonconscious information processing* (pp. 421-452). Cambridge, MA, USA: MIT Press.
- Aron, A. R. (2007). The neural basis of inhibition in cognitive control. *The Neuroscientist*, *13*, 214-228. <https://doi.org/10.1177/1073858407299288>
- Aron, A. R., Robbins, T. W., & Poldrack, R. A. (2014). Inhibition and the right inferior frontal cortex: One decade on. *Trends in Cognitive Sciences*, *18*, 177-185. <https://doi.org/10.1016/j.tics.2013.12.003>
- Bjorklund, D. F., & Harnishfeger, K. K. (1995). The role of inhibition mechanisms in the evolution of human cognition and behavior. In F. N. Dempster & C. J. Brainerd (Eds.), *New perspectives on interference and inhibition in cognition* (pp. 141-173). New York, NY, USA: Academic Press.
- Bonato, M., Fabbri, S., Umiltà, C., & Zorzi, M. (2007). The mental representation of numerical fractions: Real or integer? *Journal of Experimental Psychology: Human Perception and Performance*, *33*, 1410-1419. <https://doi.org/10.1037/0096-1523.33.6.1410>
- Borst, G., Ahr, E., Roell, M., & Houdé, O. (2015). The cost of blocking the mirror generalization process in reading: Evidence for the role of inhibitory control in discriminating letters with lateral mirror-image counterparts. *Psychonomic Bulletin & Review*, *22*, 228-234. <https://doi.org/10.3758/s13423-014-0663-9>
- Borst, G., Aïte, A., & Houdé, O. (2015). Inhibition of misleading heuristics as a core mechanism for typical cognitive development: Evidence from behavioural and brain-imaging studies. *Developmental Medicine and Child Neurology*, *57*, 21-25. <https://doi.org/10.1111/dmcn.12688>

- Borst, G., Moutier, S., & Houdé, O. (2013). Negative priming in logicomathematical reasoning. In W. De Neys & M. Osman (Eds.), *New approaches in reasoning research* (pp. 34–50). New York, NY, USA: Psychology Press.
- Borst, G., Poirel, N., Pineau, A., Cassotti, M., & Houdé, O. (2013). Inhibitory control efficiency in a Piaget-like class-inclusion task in school-age children and adults: A developmental negative priming study. *Developmental Psychology*, *49*, 1366-1374. <https://doi.org/10.1037/a0029622>
- Chi, M. T. H. (1992). Conceptual change within and across ontological categories: Examples from learning and discovery in science. In R. N. Giere (Ed.), *Cognitive models of science: Minnesota studies in the philosophy of science* (Vol. 15, pp. 129–186). Minneapolis, MN, USA: University of Minnesota Press.
- Chi, M. T. H. (2005). Commonsense conceptions of emergent processes: Why some misconceptions are robust. *Journal of the Learning Sciences*, *14*, 161-199. https://doi.org/10.1207/s15327809jls1402_1
- Diamond, A. (1998). Understanding the A-not-B error: Working memory vs. reinforced response, or active trace vs. latent trace. *Developmental Science*, *1*, 185-189. <https://doi.org/10.1111/1467-7687.00022>
- Diamond, A. (2013). Executive functions. *Annual Review of Psychology*, *64*, 135-168. <https://doi.org/10.1146/annurev-psych-113011-143750>
- diSessa, A. A. (2008). A bird's-eye view of the "pieces" vs. "coherence" controversy (from the "pieces" side of the fence). In S. Vosniadou (Ed.), *International handbook of research on conceptual change* (pp. 31-48). New York, NY, USA: Routledge.
- diSessa, A. A., & Sherin, B. L. (1998). What changes in conceptual change? *International Journal of Science Education*, *20*, 1155-1191. <https://doi.org/10.1080/0950069980201002>
- Egner, T., & Hirsch, J. (2005). Where memory meets attention: Neural substrates of negative priming. *Journal of Cognitive Neuroscience*, *17*, 1774-1784. <https://doi.org/10.1162/089892905774589226>
- Evans, J. St. B. T. (2008). Dual-processing accounts of reasoning, judgement, and social cognition. *Annual Review of Psychology*, *59*, 255-278. <https://doi.org/10.1146/annurev.psych.59.103006.093629>
- Evans, J. St. B. T., & Stanovich, K. E. (2013). Dual-process theories of higher cognition: Advancing the debate. *Perspectives on Psychological Science*, *8*, 223-241. <https://doi.org/10.1177/1745691612460685>
- Faulkenberry, T. J., & Pierce, B. H. (2011). Mental representation in fraction comparison: Holistic versus component-based strategies. *Experimental Psychology*, *58*, 480-489. <https://doi.org/10.1027/1618-3169/a000116>
- Fazio, L. K., DeWolf, M., & Siegler, R. S. (2016). Strategy use and strategy choice in fraction magnitude comparison. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *42*, 1-16. <https://doi.org/10.1037/xlm0000153>
- Frings, C., Schneider, K. K., & Fox, E. (2015). The negative priming paradigm: An update and implications for selective attention. *Psychonomic Bulletin & Review*, *22*, 1577-1597. <https://doi.org/10.3758/s13423-015-0841-4>
- Fujimura, N. (2001). Facilitating children's proportional reasoning: A model of reasoning processes and effects of intervention on strategy change. *Journal of Educational Psychology*, *93*, 589-603. <https://doi.org/10.1037/0022-0663.93.3.589>

- Gabriel, F., Coché, F., Szucs, D., Carette, V., Rey, B., & Content, A. (2012). Developing children's understanding of fractions: An intervention study. *Mind, Brain and Education: The Official Journal of the International Mind, Brain, and Education Society*, 6, 137-146. <https://doi.org/10.1111/j.1751-228X.2012.01149.x>
- Gabriel, F., Szucs, D., & Content, A. (2013a). The development of the mental representations of the magnitude of fractions. *PLOS ONE*, 8(11), Article e80016. <https://doi.org/10.1371/journal.pone.0080016>
- Gabriel, F., Szucs, D., & Content, A. (2013b). The mental representation of fractions: Adults' same-different judgments. *Frontiers in Psychology*, 4, Article 385. <https://doi.org/10.3389/fpsyg.2013.00385>
- Henik, A., & Tzelgov, J. (1982). Is three greater than five: The relation between physical and semantic size in comparison tasks. *Memory & Cognition*, 10(4), 389-395. <https://doi.org/10.3758/BF03202431>
- Houdé, O., & Borst, G. (2014). Measuring inhibitory control in children and adults. *Frontiers in Psychology*, 5, Article 616. <https://doi.org/10.3389/fpsyg.2014>
- Houdé, O., & Borst, G. (2015). Evidence for an inhibitory-control theory of the reasoning brain. *Frontiers in Human Neuroscience*, 9, Article 148. <https://doi.org/10.3389/fnhum.2015.00148>
- Houdé, O., & Guichart, E. (2001). Negative priming effect after inhibition of number/length interference in a Piaget-like task. *Developmental Science*, 4, 119-123. <https://doi.org/10.1111/1467-7687.00156>
- Houdé, O., Pineau, A., Leroux, G., Poirel, N., Perchey, G., Lanoë, C., & Mazoyer, B. (2011). Functional MRI study of Piaget's conservation-of-number task in preschool and school-age children: A neo-Piagetian approach. *Journal of Experimental Child Psychology*, 110, , 332-346. <https://doi.org/10.1016/j.jecp.2011.04.008>
- Houdé, O., Zago, L., Crivello, F., Moutier, S., Pineau, A., Mazoyer, B., & Mazoyer, N. (2001). Access to deductive logic depends on a right ventromedial prefrontal area devoted to emotion and feeling: Evidence from a training paradigm. *NeuroImage*, 14, 1486-1492. <https://doi.org/10.1006/nimg.2001.0930>
- Jasinska, A. J. (2013). Automatic inhibition and habitual control: Alternative views in neuroscience research on response inhibition and inhibitory control. *Frontiers in Behavioral Neuroscience*, 7, Article 25. <https://doi.org/10.3389/fnbeh.2013.00025>
- Jeffreys, H. (1961). *Theory of probability* (3rd ed.). Oxford, United Kingdom: Oxford University Press.
- Jordan, N. C., Hansen, N., Fuchs, L. S., Siegler, R. S., Gersten, R., & Micklos, D. (2013). Developmental predictors of fraction concepts and procedures. *Journal of Experimental Child Psychology*, 116, 45-58. <https://doi.org/10.1016/j.jecp.2013.02.001>
- Kahneman, D. (2011). *Thinking, fast and slow*. New York, NY, USA: Farrar, Strauss, Giroux.
- Krueger, F., Fischer, R., Heinecke, A., & Hagendorf, H. (2007). An fMRI investigation into the neural mechanisms of spatial attentional selection in a location-based negative priming task. *Brain Research*, 1174, 110-119. <https://doi.org/10.1016/j.brainres.2007.08.016>
- Lanoë, C., Vidal, J., Lubin, A., Houdé, O., & Borst, G. (2016). Inhibitory control is needed to overcome written verb inflection errors: Evidence from a developmental negative priming study. *Cognitive Development*, 37, 18-27. <https://doi.org/10.1016/j.cogdev.2015.10.005>

- Lechuga, M. T., Moreno, V., Pelegrina, S., Gómez–Ariza, C. J., & Bajo, M. T. (2006). Age differences in memory control: Evidence from updating and retrieval–practice tasks. *Acta Psychologica*, *123*, 279–298. <https://doi.org/10.1016/j.actpsy.2006.01.006>
- Lemaire, P., & Lecacheur, M. (2010). Strategy switch costs in arithmetic problem solving. *Memory & Cognition*, *38*, 322–332. <https://doi.org/10.3758/MC.38.3.322>
- Lortie–Forgues, H., Tian, J., & Siegler, R. S. (2015). Why is learning fraction and decimal arithmetic so difficult? *Developmental Review*, *38*, 201–221. <https://doi.org/10.1016/j.dr.2015.07.008>
- Lubin, A., Lanoë, C., Pineau, A., & Rossi, S. (2012). Apprendre à inhiber: une pédagogie innovante au service des apprentissages scolaires fondamentaux (mathématiques et orthographe) chez des élèves de 6 à 11 ans [Inhibition training: An innovative pedagogy for academic learning (mathematics and spelling) in schoolchildren aged 6 to 11 years]. *Neuroéducation*, *1*, 55–84. <https://doi.org/10.24046/neuroed.20120101.55>
- Lubin, A., Rossi, S., Lanoë, C., Vidal, J., Houdé, O., & Borst, G. (2016). Expertise, inhibitory control and arithmetic word problems: A negative priming study in mathematics experts. *Learning and Instruction*, *45*, 40–48. <https://doi.org/10.1016/j.learninstruc.2016.06.004>
- Lubin, A., Vidal, J., Lanoë, C., Houdé, O., & Borst, G. (2013). Inhibitory control is needed for the resolution of arithmetic word problems: A developmental negative priming study. *Journal of Educational Psychology*, *105*, 701–708. <https://doi.org/10.1037/a0032625>
- Meert, G., Grégoire, J., & Noël, M.-P. (2009). Rational numbers: Componential versus holistic representation of fractions in a magnitude comparison task. *Quarterly Journal of Experimental Psychology*, *62*, 1598–1616. <https://doi.org/10.1080/17470210802511162>
- Meert, G., Grégoire, J., & Noël, M.-P. (2010a). Comparing the magnitude of two fractions with common components: Which representations are used by 10– and 12–year–olds? *Journal of Experimental Child Psychology*, *107*, 244–259. <https://doi.org/10.1016/j.jecp.2010.04.008>
- Meert, G., Grégoire, J., & Noël, M.-P. (2010b). Comparing 5/7 and 2/9: Adults can do it by accessing the magnitude of the whole fractions. *Acta Psychologica*, *135*, 284–292. <https://doi.org/10.1016/j.actpsy.2010.07.014>
- Metzler, C., & Parkin, A. J. (2000). Reversed negative priming following frontal lobe lesions. *Neuropsychologia*, *38*, 363–379. [https://doi.org/10.1016/S0028-3932\(99\)00097-4](https://doi.org/10.1016/S0028-3932(99)00097-4)
- Moss, J., & Case, R. (1999). Developing children’s understanding of the rational numbers: A new model and an experimental curriculum. *Journal for Research in Mathematics Education*, *30*, 122–147. <https://doi.org/10.2307/749607>
- Munakata, Y. (1998). Infant perseveration and implications for object permanence theories: A PDP model of the A \bar{B} task. *Developmental Science*, *1*, 161–184. <https://doi.org/10.1111/1467-7687.00021>
- Namkung, J. M., & Fuchs, L. S. (2016). Cognitive predictors of calculations and number line estimation with whole numbers and fractions among at–risk students. *Journal of Educational Psychology*, *108*, 214–228. <https://doi.org/10.1037/edu0000055>
- Neill, W. T., Valdes, L. A., & Terry, K. M. (1995). Selective attention and inhibitory control of cognition. In F. N. Dempster & C. J. Brainerd (Eds.), *Interference and inhibition in cognition* (pp. 207–261). New York, NY, USA: Academic Press.

- Ni, Y., & Zhou, Y.-D. (2005). Teaching and learning fraction and rational numbers: The origins and implications of whole number bias. *Educational Psychologist*, *40*, 27-52. https://doi.org/10.1207/s15326985ep4001_3
- Obersteiner, A., Van Dooren, W., Van Hoof, J., & Verschaffel, L. (2013). The natural number bias and magnitude representation in fraction comparison by expert mathematicians. *Learning and Instruction*, *28*, 64-72. <https://doi.org/10.1016/j.learninstruc.2013.05.003>
- Perret, P., Paour, J.-L., & Blaye, A. (2003). Respective contributions of inhibition and knowledge levels in class inclusion development: A negative priming study. *Developmental Science*, *6*, 283-288. <https://doi.org/10.1111/1467-7687.00284>
- Philipp, A. M., Kalinich, C., Koch, I., & Schubotz, R. I. (2008). Mixing costs and switch costs when switching stimulus dimensions in serial predictions. *Psychological Research*, *72*, 405-414. <https://doi.org/10.1007/s00426-008-0150-x>
- Piaget, J. (1983). Piaget's theory. In P. H. Mussen (Ed.), *Handbook of child psychology* (Vol. 1, pp. 103–128). New York, NY, USA: Wiley.
- Posner, G. J., Strike, K. A., Hewson, P. W., & Gertzog, W. A. (1982). Accommodation of a scientific conception: Toward a theory of conceptual change. *Science Education*, *66*, 211-227. <https://doi.org/10.1002/sce.3730660207>
- Potvin, P., Masson, S., Lafortune, S., & Cyr, G. (2015). Persistence of the intuitive conception that heavier objects sink more: A reaction time study with different levels of interference. *International Journal of Science and Mathematics Education*, *13*, 21-43. <https://doi.org/10.1007/s10763-014-9520-6>
- Pritchard, V. E., & Neumann, E. (2009). Avoiding the potential pitfalls of using negative priming tasks in developmental studies: Assessing inhibitory control in children, adolescents, and adults. *Developmental Psychology*, *45*, 272-283. <https://doi.org/10.1037/a0014168>
- Rinne, L. F., Ye, A., & Jordan, N. C. (2017). Development of fraction comparison strategies: A latent transition analysis. *Developmental Psychology*, *53*, 713-730. <https://doi.org/10.1037/dev0000275>
- Rossi, S., Cassotti, M., Moutier, S., Delcroix, N., & Houdé, O. (2015). Helping reasoners succeed in the Wason selection task: When executive learning discourages heuristic response but does not necessarily encourage logic. *PLOS ONE*, *10*(14), Article e0123024. <https://doi.org/10.1371/journal.pone.0123024>
- Rossi, S., Lubin, A., Lanoë, C., & Pineau, A. (2012). Une pédagogie du contrôle cognitif pour l'amélioration de l'attention à la consigne chez l'enfant de 4–5 ans [A pedagogical approach of cognitive control to improve attention to instructions in preschool children]. *Neuroéducation*, *1*, 29-54. <https://doi.org/10.24046/neuroed.20120101.29>
- Schneider, M., & Siegler, R. S. (2010). Representations of the magnitudes of fractions. *Journal of Experimental Psychology: Human Perception and Performance*, *36*, 1227-1238. <https://doi.org/10.1037/a0018170>
- Siegler, R. S. (1996). *Emerging minds*. New York, NY, USA: Oxford University Press.
- Siegler, R. S., Duncan, G. J., Davis-Kean, P. E., Duckworth, K., Claessens, A., Engel, M., . . . Chen, M. (2012). Early predictors of high school mathematics achievement. *Psychological Science*, *23*, 691-697. <https://doi.org/10.1177/0956797612440101>
- Siegler, R. S., Fazio, L. K., Bailey, D. H., & Zhou, X. (2013). Fractions: The new frontier for theories of numerical development. *Trends in Cognitive Sciences*, *17*, 13-19. <https://doi.org/10.1016/j.tics.2012.11.004>

- Siegler, R. S., & Lortie-Forgues, H. (2014). An integrative theory of numerical development. *Child Development Perspectives*, 8, 144-150. <https://doi.org/10.1111/cdep.12077>
- Siegler, R. S., & Pyke, A. A. (2013). Developmental and individual differences in understanding of fractions. *Developmental Psychology*, 49, 1994-2004. <https://doi.org/10.1037/a0031200>
- Siegler, R. S., Thompson, C. A., & Schneider, M. (2011). An integrated theory of whole number and fractions development. *Cognitive Psychology*, 62, 273-296. <https://doi.org/10.1016/j.cogpsych.2011.03.001>
- Sprute, L., & Temple, E. (2011). Representations of fractions: Evidence for accessing the whole magnitude in adults. *Mind, Brain and Education: The Official Journal of the International Mind, Brain, and Education Society*, 5, 42-47. <https://doi.org/10.1111/j.1751-228X.2011.01109.x>
- Stafylidou, S., & Vosniadou, S. (2004). The development of students' understanding of the numerical value of fractions. *Learning and Instruction*, 14, 503-518. <https://doi.org/10.1016/j.learninstruc.2004.06.015>
- Stuss, D. T., Toth, J. P., Franchi, D., Alexander, M. P., Tipper, S., & Craik, F. I. (1999). Dissociation of attentional processes in patients with focal frontal and posterior lesions. *Neuropsychologia*, 37, 1005-1027. [https://doi.org/10.1016/S0028-3932\(98\)00158-4](https://doi.org/10.1016/S0028-3932(98)00158-4)
- Szűcs, D., & Soltesz, F. (2007). Event-related potentials dissociate facilitation and interference effects in the numerical Stroop paradigm. *Neuropsychologia*, 45, 3190-3202. <https://doi.org/10.1016/j.neuropsychologia.2007.06.013>
- Tipper, S. P. (1985). The negative priming effect: Inhibitory priming by ignored objects. *Quarterly Journal of Experimental Psychology*, 37, 571-590. <https://doi.org/10.1080/14640748508400920>
- Tipper, S. P. (2001). Does negative priming reflect inhibitory mechanisms? A review and integration of conflicting views. *Quarterly Journal of Experimental Psychology*, 54, 321-343. <https://doi.org/10.1080/713755969>
- Tipper, S. P., Weaver, B., Cameron, S., Brehaut, J. C., & Bastedo, J. (1991). Inhibitory mechanisms of attention in identification tasks: Time-course and disruption. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 17, 681-692. <https://doi.org/10.1037/0278-7393.17.4.681>
- Torbeyns, J., Schneider, M., Xin, Z., & Siegler, R. S. (2015). Bridging the gap: Fraction understanding is central to mathematics achievement in students from three different continents. *Learning and Instruction*, 37, 5-13. <https://doi.org/10.1016/j.learninstruc.2014.03.002>
- Ungar, L., Nestor, P. G., Niznikiewicz, M. A., Wible, C. G., & Kubicki, M. (2010). Color Stroop and negative priming in schizophrenia: An fMRI study. *Psychiatry Research: Neuroimaging*, 181, 24-29. <https://doi.org/10.1016/j.pscychresns.2009.07.005>
- Vamvakoussi, X. (2015). The development of rational number knowledge: Old topic, new insights. *Learning and Instruction*, 37, 50-55. <https://doi.org/10.1016/j.learninstruc.2015.01.002>
- Vamvakoussi, X., Van Dooren, W., & Verschaffel, L. (2012). Naturally biased? In search for reaction time evidence for a natural number bias in adults. *The Journal of Mathematical Behavior*, 31, 344-355. <https://doi.org/10.1016/j.jmathb.2012.02.001>

- Van Dooren, W., Lehtinen, E., & Verschaffel, L. (2015). Unraveling the gap between natural and rational numbers. *Learning and Instruction*, 37, 1-4. <https://doi.org/10.1016/j.learninstruc.2015.01.001>
- Van Hoof, J., Lijnen, T., Verschaffel, L., & Van Dooren, W. (2013). Are secondary school students still hampered by the natural number bias? A reaction time study on fraction comparison tasks. *Research in Mathematics Education*, 15, 154-164. <https://doi.org/10.1080/14794802.2013.797747>
- Vosniadou, S. (2013). Conceptual change in learning and instruction: The framework theory approach. In S. Vosniadou (Ed.), *The international handbook of conceptual change* (2nd ed.) (pp. 11–30). New York, NY, USA: Routledge.
- Vosniadou, S., Vamvakoussi, X., & Skopeliti, I. (2008). The framework theory approach to conceptual change. In S. Vosniadou (Ed.), *International handbook of research on conceptual change* (pp. 3–34). Mahwah, NJ, USA: Erlbaum.
- Vosniadou, S., & Skopeliti, I. (2014). Conceptual change from the framework theory side of the fence. *Science & Education*, 23, 1427-1445. <https://doi.org/10.1007/s11191-013-9640-3>
- Wright, C. I., McMullin, K., Martis, B., Fischer, H., & Rauch, S. L. (2005). Brain correlates of negative visuospatial priming in healthy children. *Psychiatry Research: Neuroimaging*, 139, 41-52. <https://doi.org/10.1016/j.psychresns.2005.03.001>

Appendix

Fraction Design

Fractions were designed so that the average distance based on the magnitude of the fractions did not differ between the common numerator items ($M = 0.65 \pm 0.71$) and the common denominator items ($M = 0.61 \pm 0.51$), $t < 1$ and so that the distance did not differ between the denominators in the common numerator items ($M = 2.7 \pm 1.9$) and the numerators in the common denominator items ($M = 2.5 \pm 1.4$), $t < 1$ (see Table A.1).

Table A.1

Pairs of Fractions Presented on the Prime and the Probe of the Test and Control Trials

Prime				Probe			
Control		Test		Control		Test	
6/7	6/3	7/2	7/8	7/3	9/3	3/7	5/7
5/4	5/8	2/7	2/9	7/3	5/3	8/6	2/6
5/3	5/7	3/7	3/2	4/3	8/3	5/3	8/3
6/2	6/9	5/7	5/6	2/9	4/9	4/6	3/6
4/9	4/2	6/5	6/3	7/5	6/5	8/7	9/7
7/8	7/5	9/7	9/4	4/5	3/5	9/8	6/8
7/2	7/9	4/5	4/7	2/6	5/6	3/4	6/4
5/6	5/2	9/7	9/8	7/4	2/4	4/8	6/8
3/2	3/4	2/3	2/4	4/7	6/7	7/8	4/8
6/4	6/7	4/9	4/3	3/2	7/2	8/5	9/5
7/9	7/6	8/6	8/5	7/2	5/2	9/5	3/5
8/3	8/9	7/4	7/3	8/2	9/2	3/2	7/2
6/8	6/5	5/3	5/8	3/6	5/6	4/9	2/9
4/3	4/8	6/8	6/7	5/9	4/9	2/9	6/9
5/9	5/4	3/2	3/6	9/4	6/4	8/6	7/6
4/5	4/3	8/7	8/9	7/4	5/4	5/7	3/7

Strategies Used to Compare Common Numerator Items

To determine the type of strategy used by adults and adolescents in common numerator items, we computed the correlation between the RTs and either the distances between the magnitudes of the fractions or by the distance between the two denominators of the two fractions in the pairs. We reasoned that if participants computed the magnitudes of the fractions to compare them, RTs should be correlated with the distance of the magnitudes of the fractions but not with the distance between the denominators and vice versa if participants compared the denominators of the fractions. In adults, we found a significant correlation between the RTs and the distance between the magnitudes of the fractions, $r(4) = -.92$, $p = .01$, but not between the RTs and the distance between the denominators of the fractions, $r(4) = -.67$, $p = .15$ (see Figure 2 A and C). In adolescents, neither of the two correlations reached significance, $r(3) = .19$, $p = .76$ between RTs and the distance between the magnitudes of the fraction and $r(4) = .33$, $p = .52$ between RTs and the distance between the denominators of the fractions (see Figure 2 B and D).

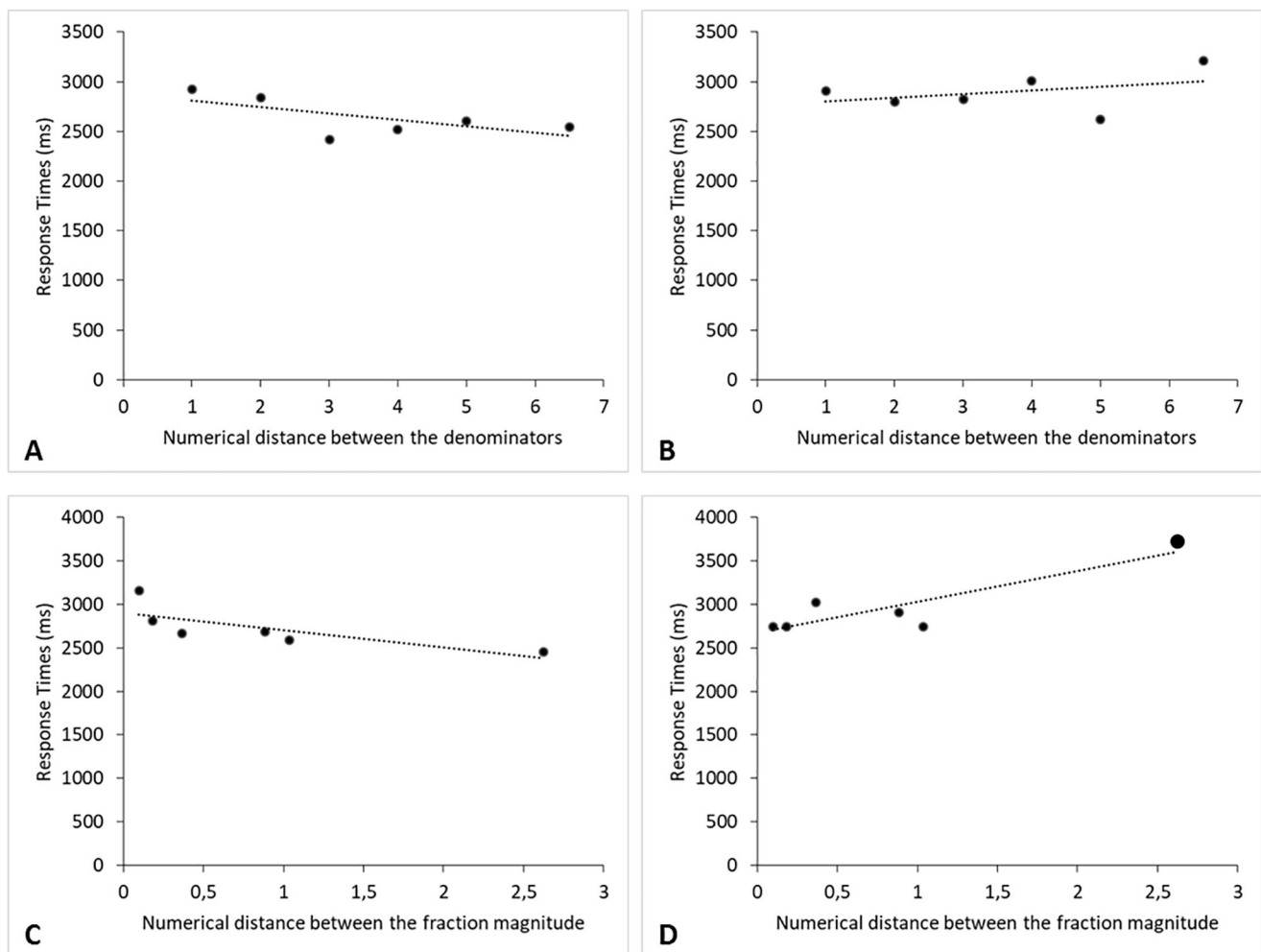


Figure 2. Mean RTs for each of the 6 different numerical distance between the denominators of the fractions (A for adults and B for adolescents) and for each of the 6 different numerical distance between the magnitude of the fractions to compare (C for adults and D for adolescents). Dot in red was considered an outlier (steam-and-leaf plot procedure) and was excluded from the correlational analysis.

Taken together these results suggest that adults required less time to perform common numerator items as the distance between the magnitudes of the two fractions increased but not as the distance between the denominators of the two frac-

tions increased. This pattern of correlations suggests that adults most likely computed the magnitudes of the two fractions to compare them, which is in line with Schneider and Siegler (2010) study that evidenced that multiple strategies can be used by adults to compare fractions. For adolescents, response times were not related to the distance between the magnitudes of the two fractions or the distances between the numerators of the two fractions. Thus, it is not entirely clear what strategies were used by the adolescents to perform the common numerator items.

Effect of Improper Fractions on Common Numerator Items Comparison and Negative Priming Effects

Six pairs of fractions on the prime of the test trials contained one proper and one improper fraction. Given that comparing such pairs could be performed without accessing the magnitude of the fractions but by choosing the fraction in which the numerator was higher than the denominator, participants might rely on different types of strategies when performing these pairs than pairs of fractions in which both of the fractions were improper or both were not improper. To determine whether participants required more time to compare two fractions in which one of the two was an improper fraction in common numerator items and whether age modulated this effect, we performed two additional ANOVAs on the prime RTs and ERs of the test trials. A two-way ANOVA of the RTs revealed that participants required less time to solve common numerator items in which one of the two fractions was an improper fraction ($M = 2942 \pm 1151$ ms) than to solve common numerator items in which both fractions were improper or both fractions were not improper ($M = 2673 \pm 916$ ms), $F(1, 48) = 8.62$, $p = .005$, $\eta_p^2 = 0.15$, $BF_{10} = 11.24$, but no effect of age, $F < 1$, $BF_{01} = 2.23$, and no interaction between age and the type of fraction, $F < 1$, $BF_{01} = 5.84$, were observed. A similar ANOVA of the ERs revealed no effect of the type of fraction, $\chi^2(1) < 1$, $BF_{01} = 1.53$, of age, $\chi^2(1) < 1$, $BF_{01} = 2.25$ and of interaction between age and the type of fraction, $\chi^2(1) < 1$, $BF_{01} = 5.04$ for the interaction.