Adolescents and Adults Need Inhibitory Control to Compare Fractions

Sandrine Rossi[*a], Julie Vidal[b], Marie Letang[b], Olivier Houdé[c], Grégoire Borst[c]

[a] LPCN EA 7452 - Maison de la Recherche en Sciences Humaines USR3486 CNRS, Département de Psychologie, Université de Caen Normandie, Caen, France

[b] LaPsyDE UMR 8240 – CNRS, Département de Psychologie, Université Paris Descartes, Paris, France

[c] Institut Universitaire de France, Paris, France

Corresponding Author's Contact Adress

Université de Caen Normandie

UFR de Psychologie

Esplanade de la Paix CS 14032

14032 Caen Cedex 5, France

sandrine.rossi@unicaen.fr

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, whole number bias, inhibitory control

According to dual-process theories of human thinking (Evans, 2008; Kahneman, 2011; Evans & Stanovich, 2013), 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, Aite, & 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 explains not only systematic errors in logical Piagetian problems but also systematic difficulties faced by children in the literacy classroom (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). For instance, children have difficulty solving arithmetic word problems such as Bill has 20 marbles. He has 5 more marbles than John. How many marbles does John have? Here, the relational term (i.e., more than) is inconsistent with the required arithmetic operation (i.e., subtraction) to perform. Most errors in these types of problems are reversal errors characterized by adding the numbers instead of subtracting them or vice versa (e.g., Stern, 1993). Two studies provided convergent evidence that the ability to solve this type of arithmetic word problem is rooted, in part, in the ability to inhibit the "add if more, subtract if less" misleading heuristics in children, adolescents, adults (Lubin et al., 2013) and even mathematics experts (Lubin et al., 2016). Similar to the resolution of an arithmetic word problem, the inhibition of a misleading heuristic is also needed to overcome systematic errors in reading, particularly for mirror errors, i.e., confusion between letters that are mirror images of each other (i.e., such as b and d). These mirror errors are likely the result of the mirror generalization process that allows one to identify a visual stimulus regardless of its presentation side, a process that is advantageous for objects but not for letter recognition (Lachmann & van Leeuwen, 2007). Two studies converged in showing that novice and expert readers need to inhibit the mirror generalization process to discriminate letters that are mirror images of each other (Ahr et al., 2016; Borst et al., 2015).

Most of these studies used a negative priming paradigm to determine whether the inhibition of a misleading heuristic is needed to solve classical Piagetian tasks (e.g., Borst, et al., 2013; Houdé & Guichart, 2001; Perret et al., 2003) and school learning tasks (e.g., Ahr et al., 2016; Borst et al., 2015; Lanoë et al., 2016; Lubin et al., 2013; Potvin et al., 2015). 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 et al., 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 et al., 2015; Lanoë et al., 2016; Lubin et al., 2013; Lubin et al., 2016; Potvin et al., 2015).

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). 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 (Stafilydou & 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.

This common error observed in fraction comparison is referred to as 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). According to some conceptual change theories (Chi, 1992, 2005; diSessa, 2008; diSessa & Sherin, 1998; Posner, Strike, Hewson, & Gertzog, 1982; Vosniadou, Vamvakoussi & Skopeliti, 2008; Vosniadou, 2013; Vosniadou & Skopeliti, 2013), the concept of a natural number can coexist with the concept of a rational number. Because the two concepts coexist, the concept of a natural number might interfere with the concept of a rational number in certain contexts, resulting in a natural number bias. It can interfere with mathematical reasoning in some specific contexts, such as fraction comparison problems, in part because natural number properties are often erroneously generalized to rational numbers. 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) and using the "greater the whole number, the greater the fraction" heuristic, particularly 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 achievements (Siegler & Lortie-Forgues, 2014) and for the development of conceptual and procedural knowledge of fractions in particular (e.g., Rinne, Ye, & Jordan, 2017).

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). For example, children with a partial understanding of fractions (i.e., choosing fractions with smaller numbers in a fraction comparison task) at grade 4 are more likely to adopt the correct strategy to compare fractions at grade 6 than those displaying a larger "whole number bias" at grade 4 (Rinne et al., 2017). In addition, adults tend to represent fractions as discrete magnitudes when simpler strategies are not pertinent (Rinne et al., 2017; Fazio et al., 2016). Taken together, these findings are in line with the overlapping wave theory proposed by Siegler (1996).

Van Dooren, Lehtinen, & 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 misleading heuristic (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, Szuc & Content, 2013b; Meert, Grégoire, & Noël, 2010b), adolescents (Van Hoff 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 heuristic (Faulkenberry & Pierce, 2011; Gabriel, Szuc & Content, 2013a; Schneider & Siegler, 2010; Sprute & Temple, 2011). This assumption is in line with findings that several factors can lead to the whole number bias observed in fraction comparison tasks (Alibali & Sydney, 2015). In particular, whole number bias would arise in certain contexts at certain ages when rational number representations are not sufficiently precise or sufficiently activated to solve the problem. The strength of these rational number representations is 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 also affects fraction magnitude abilities as rational and whole number representations become increasingly more precise over time (see Siegler et al., 2011).

Taken together, findings from 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.

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. Note that some studies demonstrated that the inhibition of contextual or perceptual cues contributes to the ability to compare fractions. For example, Siegler & 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 or the location of the number (see, e.g., Szucs & 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 and

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 using a negative priming approach.

In the present study, we designed a variant of the negative priming paradigm originally designed by Tipper (1985). In our negative priming paradigm, we asked adolescents and adults to compare the magnitude of two fractions with common denominators (e.g., 4/8 vs. 5/8) on probes, a context in which the "greater the whole number, the greater the fraction" strategy provides the correct answer (i.e., stating that 5/8 is larger than 4/8 because 5 > 4). Importantly, in the test condition, probes are preceded by primes in which adolescents and adults compared fractions with common numerators (e.g., 1/4 vs. 1/5) on the primes before the probes—a context in which, according to our hypothesis, the "greater the whole number, the greater the fraction" strategy should be inhibited to avoid committing an error (i.e., stating that 1/5 is larger than 1/4 because 5 > 4). In the control condition, probes were preceded by primes in which the inhibition of the "greater the whole number, the greater the fraction" strategy was not required. Participants were simply asked to determine which of the two fractions presented a denominator that was larger than the numerator. 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 fractions with common numerators (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 fractions with the same numerator 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 fractions with the same numerator 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 et al., 2013; Lanoë et al., 2016).

Method

Participants

Thirty-six typically developing adolescents (mean age ± 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 university students (21 ± 1.7 years, 17 women) without cognitive impairment participated in the study. All students were typical university students who had all obtained their high school diplomas. The two groups differed significantly in age ($t_{(67)} = 21.4$, $p < .0001$, Cohen’s $d = 4.91$) but not in sex repartition ($X^2_{(1)} = 0.38$, $p = .53$).

By definition, negative priming effects can be observed only if participants accurately compared fractions with a common numerator (i.e., the prime). Therefore, 15 adolescents (41 % of the sample, M = 72.3 ± 19.2 % of errors in common numerator fraction comparison items) and 2 adults (6 %, M = 63.4 ± 4.8 of errors in common numerator fraction comparison items) were excluded from the analysis because they performed at chance levels of performance (see Table 2). 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 ± 13.5 % of errors in common numerator fraction comparison items) and 30 adults (mean age: 21 ± 1.8 years, 14 women, M = 16 ± 16.2 % of errors in common numerator fraction comparison items). The gender distribution did not differ between the two groups ($X^2_{(1)} = 0.01$, $p = .90$).

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: fractions with common denominator items, fractions with common numerator items and denominator-numerator comparison items. In the fractions with common denominator items (e.g., 2/4 *vs.* 5/4) and fractions with 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 fractions with common numerator items. In the denominator-numerator comparison 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 comparison items. Note that the two fractions presented in the denominator-numerator comparison items had the same numerator (e.g., 4/2 *vs.* 4/5) as the fractions with 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 Table 1). Fractions were designed so that the average distance based on the magnitude of the fractions did not differ between the common numerator problems ($M = 0.65 \pm 0.71$) and the common denominator problems ($M = 0.61 \pm 0.51$), $t < 1$ and so that the distance did not differ between the denominators in the common numerator problems ($M = 2.7 \pm 1.9$) and the numerators in the common denominator problems ($M = 2.5 \pm 1.4$), $t < 1$.

We presented 24 items (eight of each type) for the practice trials and 96 (32 fractions with common denominator items, 16 fractions with common numerator items, and 16 denominator-numerator comparison items) for the experimental trials.

Table 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

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 fractions with common denominator items and finishing with the fractions with 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 fraction with a common numerator item (as a prime) and then a fraction with a common denominator item (as a probe). In the control trials, participants performed a denominator-numerator comparison 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.

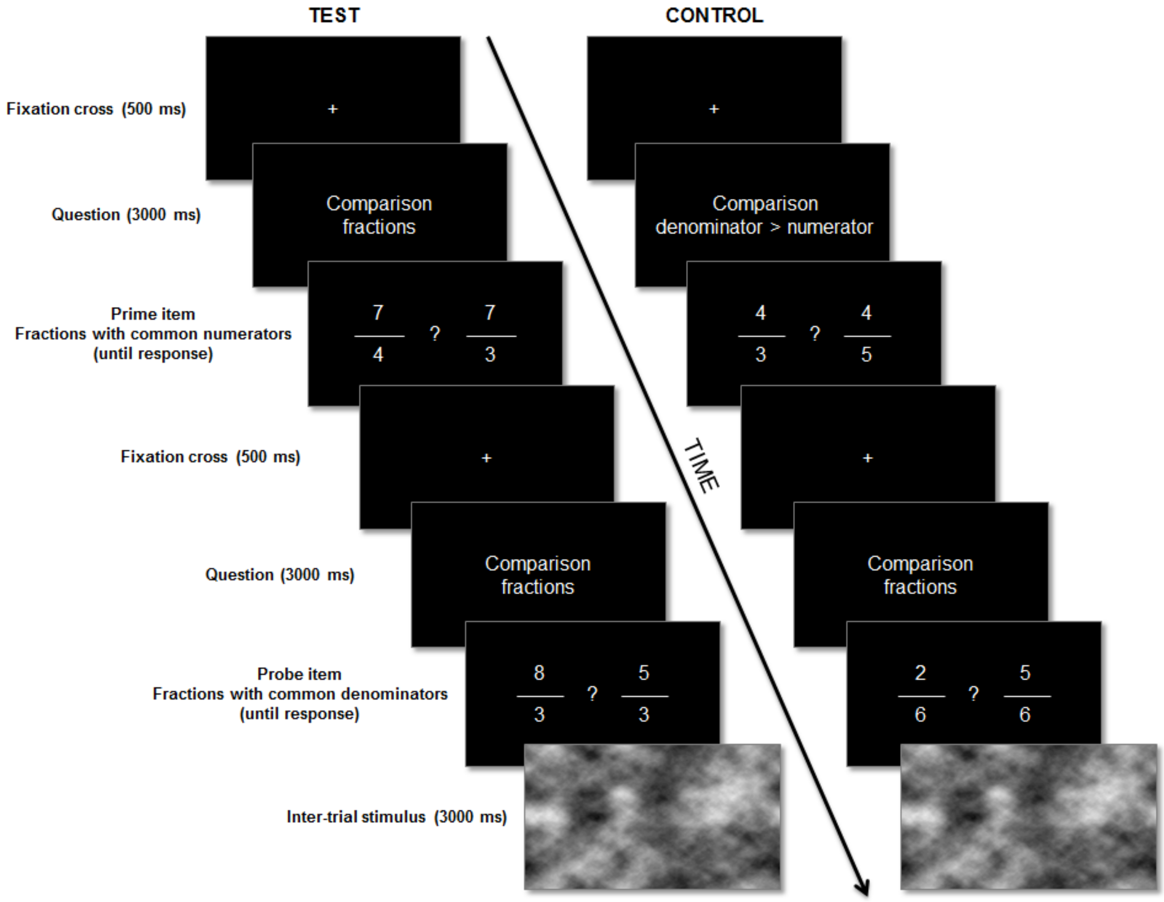

Figure 1

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

This 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, as shown in Figure 1, 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) 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) 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) 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).

Each trial started with the presentation of a fixation point (500 ms) followed by a 3000 ms presentation of the type of comparison (fraction magnitude comparison *vs.* denominator-numerator comparison) participants needed to perform on the next item. “Fraction magnitude comparison” or “denominator-numerator comparison” 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 for 500 ms, followed by a 3000 ms 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 for 3000 ms 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. 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 2). 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 hypothesis with Bayes Factor (BF_{01}) higher than 3 providing substantial evidence for the null hypothesis (Jeffreys, 1961).

Table 2

Means and standard deviations (in parentheses) of ERs (%) and RTs (ms) in adolescents and adults.

			Adolescents		Adults	
			Included (n = 20)	Excluded (n = 14)	Included (n = 30)	Excluded (n = 2)
			M (SD)	M (SD)	M (SD)	M (SD)
ERs	Prime	Test	16.3 (13.5)	72.3 (19.2)	16 (16.2)	63.4 (4.8)
		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)
		Control	12.2 (12.9)	28.1 (23.7)	8.7 (11.8)	31.3 (8.8)
RTs	Prime	Test	3080 (960)		2612 (1082)	
		Control	1751 (693)		1288 (487)	
	Probe	Test	2729 (863)		2420 (1010)	
		Control	2538 (859)		2287 (960)	
	Negative priming		192 (392)		134 (426)	

Primes analyses

The two-way mixed design ANOVA on the ERs revealed a main effect of the type of trial, $F(1, 48) = 7.76$, $p = .007$, $\eta^2_p = .14$ but not of age, $F(1, 48) = 1.48$, $p = .23$ or a two-way interaction between the type of trial and age, $F(1, 48) = 1.48$, $p = .23$, $BF_{01} = 0.63$. Adults and adolescents committed more errors when comparing fractions with common numerators (test trials: 16.2 ± 2.1 %) than when comparing which fraction had a denominator larger than the numerator (control trials: 9.5 ± 1.2 %).

A two-way mixed design ANOVA of the RTs revealed a main effect of the type of trial—with participants requiring more time to perform fractions with common numerator items (M = 2846 ± 150 ms) than denominator-numerator items (M = 1519 ± 83 ms), $F(1, 48) = 112.35$, $p < .0001$, $\eta^2_p = .70$—and a main effect of age, $F(1, 48) = 5.05$, $p = .02$, $\eta^2_p = .09$—with adults (M = 1950 ± 131 ms) faster than adolescents (M = 2415 ± 161 ms) but no two-way interactions, $F < 1$, $BF_{01} = 28.93$.

To determine the type of strategy used by adults and adolescents in common numerator problems, 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. In adults, we found a significant correlation between the RTs and the distance between the magnitudes of the fractions, $r(4) = -.92$, $p = .005$, but not between the RTs and the distance between the denominators of the fractions, $r(4) = -.67$, $p = .15$. In adolescents, neither of the two correlations reached significance, $r(4) = -.66$, $p = .15$ 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.

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 problems 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 problems in which one of the two fractions was an improper fraction (M = 2942 ± 1151 ms) than to solve common numerator problems in which both fractions were improper or both fractions were not improper (M = 2673 ± 916 ms), $F(1, 48) = 8.62$, $p = .005$, $n^2p = 0.15$, but no effect of age, $F < 1$, and no interaction between age and the type of fraction, $F < 1$, $BF_{01} = 3.72$, were observed. A similar ANOVA of the ERs revealed no effect of the type of fraction, of age and of interaction between age and the type of fraction, all Fs < 1, $BF_{01} = 2.08$ for the interaction.

Probes analyses

The two-way mixed design ANOVA on the ERs revealed no main effect of the two types of trials, $F(1, 48) = 1.48$, $p = .23$, of age, $F< 1$, and no two-way interaction, $F < 1$, $BF_{01} = 3.11$ suggesting substantial evidence in favor of the null hypothesis. Thus, 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, $F(1, 48) = 7.46$, $p < .008$, $\eta^2_p = .13$, but no effect of age, $F(1, 48) = 1.12$, $p = .29$, and no two-way interaction, $F < 1$, $BF_{01} = 3.20$. Importantly, we found that adolescents and adults required more time to perform fractions with common denominator items preceded by fractions with common numerator items (test trials: M = 2730 ± 863 ms for adolescents and 2421 ± 1010 ms for adults) than those preceded by a denominator-numerator comparison item (2538 ± 859 ms for adolescents and M = 2287 ± 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.

Given that participants required less time to perform common numerator problems in which one of the two fractions was improper (on the prime), suggesting that participants might solve these problems without accessing the magnitude of the fractions but by choosing the fraction in which the numerator was higher than the denominator, one could argue that the negative priming effect could be driven by this type of common numerator problem. To determine whether the negative priming effects reported in adolescents and adolescents on the common denominator problems are driven by the common numerator problems in which one of the two fraction are improper, we ran additional analyses in which we excluded test trials with common numerator problems in which one of the two fractions was improper. A two-way ANOVA of the probe RTs revealed a main effect of the type of fraction, $F (1, 48) = 12.7$, $p < .001$, $n^2_p = 0.21$, but no effect of age, $F < 1$, and no two-way interaction, $F < 1$, $BF_{01} = 3.09$. Importantly, adolescents and adults required more time to perform the common denominator problems in the test ($M = 2814 \pm 854$ ms for adolescents and $M = 2640 \pm 1177$ ms for adults) than in the control ($M = 2548 \pm 864$ ms for adolescents and $M = 2388 \pm 1066$ ms for adults) trials, $t(19) = 2.68$, $p < .025$, $d = 0.31$ for adolescents and $t(29) = 2.56$, $p < .025$, $d = 0.22$ for adults. A similar ANOVA of the probe ERs revealed no effect of the type of trials, $F (1, 48) = 3.05$, $p = .08$, of age, $F < 1$, and no two-way interaction, $F < 1$, $BF_{01} = 2.21$.

Primes vs. probes analyses

Finally, to verify whether adults and adolescents had more difficulty comparing fractions with common numerators than fractions with common denominators, we conducted a 2 (type of fraction: common numerators *vs.* common denominators) x 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., fractions with common numerators) and for probes in the control trials (i.e., fractions with common denominators). 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 and were less accurate 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), $F(1, 48) = 5.30$, $p = .026$, $\eta_p^2 = .10$ for ERs and $F(1, 48) = 31.11$, $p < .0001$, $\eta_p^2 = .39$ for RTs.

We found no main effect of age, $F < 1$ for ERs and $F(1, 48) = 1.74$, $p = .19$ for RTs, and no significant interaction between the type of fraction and age, $F < 1$, $BF_{01} = 3.02$, for ERs and $F(1, 48) = 1.96$, $p = .17$, $BF_{01} = 1.88$, for RTs.

Excluded vs. included adolescent analyses

To provide information regarding the specific difficulties faced by adolescents that were excluded from our sample, we performed a 2 (type of trial: test or control) x 2 (group: excluded or included adolescents) analysis of variance (ANOVA) of the prime ERs that revealed a significant effect of the type of trial, $F(1, 34) = 56.9$, $p < .001$, $\eta p2 = .62$, a significant effect of group, $F(1, 34) = 57.6$, $p < .001$, $\eta p2 = .63$ and a significant two-way interaction between the type of trial and group, $F(1, 34) = 43.6$, $p < .001$, $\eta p2 = .56$. Excluded adolescents were less accurate than included adolescents on the common numerator problems (27.7 % ± 4 % *vs.* 83.7 % ± 3.6 %; $t\,(34) = 10.25$, $p < .001$, $d = 14.7$) but not on the control primes (84.4 % ± 4.2 % *vs.* 87.5 % ± 3.8 %; $t < 1$). A similar ANOVA of the probe ERs revealed a main effect of group, $F\,(1, 34) = 10.17$, $p < .005$, $\eta p2 = .23$, with excluded adolescents being less accurate than included adolescents on the probe trials (72 % ± 3.9 % *vs.* 89 % ± 3.5 %). In addition, we found no main effect of the type of trials on ERs, $F < 1$, and no two-way interaction between these factors, $F < 1$, $BF_{01} = 3.97$. Taken together, these results suggest that excluded adolescents were impaired in their ability to perform common numerator and denominator problems in the context of a negative priming paradigm.

Discussion

In the present study, we investigated (a) whether inhibitory control is required to compare fractions with common numerators 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 fractions with common numerators (i.e., the whole number bias) increases between adolescents and adults. In line with previous studies on adolescents (Van Hoff, 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 fractions with common numerators than fractions with common denominators, 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 problems 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 fraction with common numerators 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 fractions with common denominators 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 fractions with common numerators. 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., Szucs & Soltesz, 2007), might also be important to compare such fractions.

Importantly, we found that adults required less time to perform common numerator problems as the distance between the magnitudes of the two fractions increased but not as the distance between the denominators of the two fractions 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 previous studies (e.g., Bonato et al., 2007 but see Schneider & Siegler, 2010, for evidence 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 fractions.

A verbal report could have provided such information. Indeed, a number of studies have assessed the type of strategies participants rely on to compare fractions (or perform arithmetic operations with fractions) by asking participants how they solve each problem (see, e.g., Schneider & Siegler, 2010; Siegler & Pyke, 2013; Siegler et al., 2011). These studies have demonstrated the validity of such verbal reports for studying the strategies used by children, adolescents and adults to compare the magnitude of fractions (Schneider & Siegler, 2010) and the development of fraction understanding (Siegler & Pyke, 2013). For example, Schneider & Siegler (2010) used verbal reports to provide evidence that participants could rely on componential strategy to compare fractions with common numerators. The negative priming paradigm, by definition, precludes any verbal reports on a problem by problem basis because the negative priming effect can be observed only within a short period of time (up to 6 seconds, e.g., Tipper, Weaver, Cameron, Brehaut, & Bastedo, 1991). The lack of verbal reports on the type of strategy used by the participants to solve the common numerator and common denominator problems is a clear limitation of the present study because the negative priming effect provides information on the strategy that was inhibited but not on the strategy that was activated afterward.

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 problems, 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; Borst et al., 2012, Lubin et al., 2013; Lubin et al., 2016; Borst et al., 2015; Ahr et al., 2016).

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 these skills improve with instruction and age. Moreover, in the context where the two fractions have the same numerators, the development of fraction comparison skills could be related in part to the progressive ability to inhibit a misleading strategy. 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 et al., 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. This assumption is consistent with the fact that inhibitory control efficiency continues to improve from childhood to late adolescence, in part due to the slow maturation of the prefrontal cortex until early adulthood (Casey et al., 1997; Casey, Tottenham, Liston, & Durston, 2005; Dagenbach & Carr, 1994; Diamond, 2002; Houdé et al., 2011).

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 adolescents were less efficient than adults at comparing fractions with common numerators. 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 as early as ninth grade, presumably due to intense 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 necessary at all ages to compare fractions with common numerators. Our finding complements other findings reported in literacy (Ahr et al., 2016; Borst et al., 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). That said, one could argue that using decimal numbers rather than fractions might prevent the implicit transfer of the whole number properties to rational numbers. However, the comparison of decimal numbers seems also to be affected by the whole number bias, particularly in a context in which the smallest number has the greatest number of digits after the decimal point (1.345 vs. 1.4) (e.g., Roche, 2005; Sackur-Grisvard & Léonard, 1985; Van Dooren et al., 2015). In this context, children erroneously think that 1.345 is larger than 1.4 because 345 is larger than 4. A recent negative priming study actually provided evidence that 7th graders must inhibit the whole number bias to compare decimal numbers in which the smallest number has the greatest number of digits after the decimal point (1.345 vs. 1.4) (Roell, Viarouge, Houdé & Borst, 2017).

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 fractions with common numerators. 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 problems. 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 the common numerator problems, 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.

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; Moss & Case, 1999; Gabriel et al, 2012). 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.

Our finding complements other findings that show that inhibitory control is critical to avoid being systematically biased in contexts in which a heuristic interferes with more adapted strategies in different cognitive and educational domains—such as categorization (Borst et al., 2013; Perret et al., 2003), numbers (e.g., Houdé & Guichart, 2001; Houdé et al., 2011), and logical reasoning (Houdé et al., 2000; Rossi et al., 2015)—and in school learning, such as literacy (Ahr et al., 2016; Borst et al., 2015; Lanoë et al., 2016), mathematics (Lubin et al., 2013) and science (Potvin et al., 2015). Taken together, these findings suggest that conceptual change in various domains does not rely exclusively on the growing ability to coordinate multiple systems of operations (Piaget, 1983) but also on the growing ability to inhibit misleading strategies (Diamond, 1991; Houdé, 2000; Houdé & Borst, 2014, 2015; for a review see Borst, Aïte, and Houdé, 2015).

One of the critical questions that remains to be investigated is the degree of generality or specificity of the inhibitory control processes involved in all of these cognitive domains. Previous studies have provided evidence that some tasks rely on similar inhibitory control processes in 10-year-old children as shown by conflict adaptation (a) between a numerical (i.e., Piaget’s number-conservation task) and a categorization (i.e., Piaget’s class-inclusion task) tasks (Borst, Poirel, Pineau, Cassotti, & Houdé, 2012) and (b) between a semantic (i.e., Color-Word Stroop task) and a numerical (i.e., Piaget’s number-conservation task) task (Linzarini, Houdé, & Borst, 2015). Further studies are needed to determine (a) whether inhibitory control processes are similar regardless of the inhibitory heuristic and the cognitive domain considered and (b) whether the generality and specificity of inhibitory control of misleading heuristics change with age and/or expertise (see Aite, Cassotti, Linzarini, Osmont, Houdé, & Borst, in press for preliminary evidence of a growing specificity of inhibitory control processes with age).

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, providing feedbacks during the practice trials might prevent discussing how participants would behave in a more classical educational context. Indeed, providing feedbacks could constitute a minimal form of education to the participants and thus change their spontaneous choice of strategy in a given context. That said, we note that even if feedback was provided in the practice trials, 41 % of adolescents and 2 % 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).

Finally, the sample size in the present study might be too small to detect a significant age effect on the amplitude of the negative priming effect. Note, however, that (a) the sample size 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 et al, 2013; Lanöe et al., 2016). In addition, the Bayes statistics on the interaction effects on the probe responses times and error rates provided substantial evidence in favor of the null hypothesis suggesting that the small sample size was unlikely at the root of the lack of interaction effects reported on the probe.

In light of these potential limitations, future studies should 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.

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).

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. doi: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. doi:10.1111/cdev.12558

Aïte, A., Cassotti, M., Linzarini, A., Osmont, A., Houdé, O., & Borst, G. (2018). Adolescents' inhibitory control: Keep it cool or lose control. *Developmental Science, 21, 1,* e12491. doi:10.1111/desc.12491

Alibali, M. W., & Sidney P. J. (2015). Variability in the natural number bias: Who, when, how, and why. *Learning & Instruction, 37*, 56-61. doi: 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. Umilta & M. Moscovitch (Eds). *Attention and Performance XV:*

Conscious and Nonconscious information processing (pp. 421–452). Cambridge, MA: MIT Press.

Aron, A., Robbins, T., & Poldrack, R. (2014). Inhibition and the right inferior frontal cortex: one decade on. *Trends in Cognitive Science, 18,* 177-185. doi: 10.1016/j.tics.2013.12.003.

Bailey, D. H., Zhou, X., Zhang, Y., Cui, J., Fuchs, L. S., Jordan, N. C., Gersten, R., & Siegler, R. S. (2012). Competence with fractions predicts gains in mathematics achievement. *Journal of Experimental Child Psychology, 113,* 447–455. doi:10.1016/j.jecp.2014.08.006

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: 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. doi: 10.1037/0096-1523.33.6.1410

Borst, G., Poirel, N., Pineau, A., Cassotti, M., & Houdé, O. (2012). Inhibitory control in number-conservation and class-inclusion tasks: A neo-Piagetian inter-tasks priming study. *Cognitive Development, 27,* 283-298. Doi: 10.1016/j.cogdev.2012.02.004

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: Psychology Press.

Borst, G., Pineau, A., Poirel, N., 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. doi: 10.1037/a0029622

Casey, B. J., Tootenham, N., Liston, C., & Durston, S. (2005). Imaging the developing brain: what have we learned about cognitive development? *Trends in Cognitive Science, 9,* 104–110. doi:10.1016/j.tics.2005.01.011

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. doi: 10.3758/s134223-014-0663-9

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 & Child Neurology, 57,* 21–25. doi: 10.1111/dmcn.12688

Casey, B. J., Trainor, R. J., Orendi, J. L., Schubert, A. B., Nystrom, L. E., Giedd, J. N., Castellanos, F. X., Haxby, J. V., Noll, D. C., Cohen, J. D., Forman, S. D., Dahl, & R. E., Rapoport, J. L. (1997). A Developmental Functional MRI Study of Prefrontal Activation during Performance of a Go–No–Go Task. *Journal of Cognitive Neuroscience, 9,* 835–847. doi: 10.1162/jocn.1997.9.6.835

Chi, M. T. H. (1992). Conceptual change within an 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: University of Minnesota Press.

Chi, M. T. H. (2005). Commonsense conceptions of emergent processes: Why some misconceptions are robust. *The Journal of the Learning Sciences, 14,* 161-199. Doi: 10.1207/s15327809jls1402_1

Dagenbach, D., & Carr, T.H. (Eds.). (1994). *Inhibitory Processes in Attention, Memory, and Language.* San Diego, CA: Academic Press.

Diamond, A. (1991). Neuropsychological insights into the meaning of object concept development. In S. Carey & R. Gelman (Eds.), *The Epigenesis of mind: Essays on biology and cognition* (pp. 67–110). Hillsdale, NJ: Erlbaum.

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. doi:10.1111/1467-7687.00022

Diamond, A., Kirkham, N., & Amso, D. (2002). Conditions under which young children can hold two rules in mind and inhibit a prepotent response. *Developmental Psychology, 38,* 352–362. doi: 10.1037//0012-1649.38.3.352

Diamond, A. (2013). Executive functions. *Annual Review of Psychology, 64,* 135–168. doi: 10.1146/annurev-psych-113011-143750

diSessa, A. A., & Sherin, B. L. (1998). What changes in conceptual change? *International Journal of Science Education, 20,* 1155-1191. Doi: 10.1080/0950069980201002

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. New York, NY: Routledge.

Egner, T., & Hirsch, J. (2005). Where memory meets attention: Neural substrates of negative priming. *Journal of Cognitive Neuroscience, 17,* 1774–1784. Doi: 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. doi: 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. doi: 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. doi: 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.

Frings, C., Schneider, K. K., & Fox, E. (2015). The negative priming paradigm: An update and implications for selective attention. *Psychonomic Bulletin and Review, 22,* 1577-1597. DOI: 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. doi: 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, 6,* 137–146. doi: 10.1111/j.1751-228X.2012.01149.x

Gabriel, F., Coché, F., Szucs, D., Carette, V., Rey, B., & Content, A. (2013). A componential view of children's difficulties in learning fractions. *Frontiers in Psychology, 4*: 715. doi: 10.3389/fpsyg.2013.00715

Gabriel, F., Szucs, D., & Content, A. (2013a). The mental representation of fractions: adults' same–different judgments. *Frontiers in Psychology, 4*: 385. doi: 10.3389/fpsyg.2013.00385

Gabriel, F., Szucs, D., & Content, A. (2013b). The development of the mental representations of the magnitude of fractions. *PloS ONE, 8(11)*: e80016. doi:10.1371/journal.pone.0080016

Houdé, O. (2000). Inhibition and cognitive development: Object, number, categorization, and reasoning. *Cognitive Development, 15,* 63–73. doi:10.1016/S0885-2014(00)00015-0

Houdé, O., & Guichart, E. (2001). Negative priming effect after inhibition of number/length interference in a Piaget–like task. *Developmental Science, 4,* 119–123. doi: 10.1111/1467-7687.00156

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. doi:10.1006/nimg.2001.0930

Houdé, O., Pineau, A., Leroux, G., Poirel, N., Perchey, G., Lanoë, C., Lubin, A., Turbelin, M.–R., Rossi, S., Simon, G., Delcroix, N., Lamberton, F., Vigneau, M., Wisniewski, G., Vicet, J.–R., & 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. doi:10.1016/j.jecp. 2011.04.008

Houdé, O., & Borst, G. (2014). Measuring inhibitory control in children and adults. *Frontiers in Psychology, 5:616*. doi:10.3389/fpsyg.2014. 00616

Houdé, O., & Borst, G. (2015). Evidence for an inhibitory–control theory of the reasoning brain. *Frontiers in Human Neuroscience, 9:148*. doi: 10.3389/fnhum.2015.00148

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*. doi: 10.3389/fnbeh.2013.00025.

Jeffreys, H. (1961). *Theory of probability* (3rd Ed.). Oxford, UK: 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,* 45–59. doi: 10.1016/j.jecp.2013.02.001

Kahneman, D. (2011). *Thinking, Fast and Slow*. New York: 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. doi:10.1016/j.brainres.2007.08.016

Lachmann, T., & van Leeuwen, C. (2007). Paradoxical enhancement of letter recognition in developmental dyslexia. *Developmental Neuropsychology, 31*, 61–77.

Lanoë, C., Lubin, A., Vidal, J., 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. doi: 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. doi:10.1016/j.actpsy.2006.01.006

Lemaire, P. & Lecacheur, M. (2010). Strategy switch costs in arithmetic problem solving. *Memory & Cognition, 38*, 322–332. doi:10.3758/MC.38.3.322

Linzarini, A., Houdé, O., & Borst, G. (2015). When Stroop helps Piaget: An inter-task positive priming paradigm in 9-year-old children. *Journal of Experimental Child Psychology, 139*, 71–82. Doit: 10.1016/j.jecp.2015.05.010

Lortie–Forgues, H., Tian, J., & Siegler, R. S. (2015). Why is learning fraction and decimal arithmetic so difficult? *Developmental Review, 38,* 201–221. doi: 10.1016/j.dr.2015.07.008

Lubin, A., Lanoë, C., Pineau, A., & Rossi, S. (2012). Inhibition training: An innovative pedagogy for academic learning (mathematics and spelling) in schoolchildren aged 6 to 11 years (title in French: Apprendre à inhiber : une pédagogie innovante au service des apprentissages scolaires fondamentaux (mathématiques et orthographe) chez des élèves de 6 à 11 ans). *Neuroéducation, 1,* 55–84.

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. doi: 10.1037/a0032625

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*. doi: 10.1016/j.learninstruc.2016.06.004

Meert, G., Grégoire, J., & Noël, M.–P. (2009). Rational numbers: Componential versus holistic representation of fractions in a magnitude comparison task. *The Quarterly Journal of Experimental Psychology, 62,* 1598–1616. doi: 10.1080/17470210802511162

Meert, G., Grégoire, J., & Noël, M.–P. (2010a). Comparing 5/7 and 2/9: Adults can do it by accessing the magnitude of the whole fractions. *Acta Psychologica, 135,* 284–292. doi:10.1016/j.actpsy.2010.07.014

Meert, G., Grégoire, J., & Noël, M.–P. (2010b). 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. doi:10.1016/j.jecp.2010.04.008

Metzler, C., & Parkin, A. J. (2000). Reversed negative priming following frontal lobe lesions. *Neuropsychologia, 38,* 363–379. Doi: 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 of Research in Mathematics Education, 30,* 122–147.

Munakata, Y. (1998). Infant perseveration and implications for object permanence theories: A PDP model of the A-not-B task. *Developmental Science, 1*, 161-211.

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. doi: 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: 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. doi: 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,* 64e72. doi: 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. doi: 10.1111/1467-7687.00284

Philipp, A., Kalinich, C., Koch, I., & Schubotz, R. (2008). Mixing costs and switch costs when switching stimulus dimensions in serial predictions. *Psychological Research, 72*, 405–414.

Piaget, J. (1983). Piaget's theory. In P. H. Mussen (Ed.), *Handbook of Child Psychology* (Vol. 1, pp. 103–128). NewYork: 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. Doi: 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.

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. doi:10.1037/0012-1649.40.2.191

Rinne, L. F., Ye, A., & Jordan, N. C. (2017). Development of Fraction Comparison Strategies: A Latent Transition Analysis. *Developmental Psychology*, *53,* 713–730, http://dx.doi.org/10.1037/dev0000275

Roche, A. (2005). Longer is Larger--Or is It? *Australian Primary Mathematics Classroom, 10*, 11-16.

Roell, M., Viarouge, A., Houdé, O., & Borst, G. (2017). Inhibitory control and decimal number comparison in school-aged children. *PLOS ONE,* 12(11): e0188276. https://doi.org/10.1371/journal.pone.0188276

Rossi, S., Lubin, A., Lanoë, C., & Pineau, A. (2012). A pedagogical approach of cognitive control to improve attention to instructions in preschool children (title in French: Une pédagogie du contrôle cognitif pour l'amélioration de l'attention à la consigne chez l'enfant de 4–5 ans). *Neuroéducation, 1*, 29–54.

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 not necessarily encourages logic. *PLoS ONE, 10(14)*: e0123024. doi:10.1371/journal.pone.0123024

Sackur-Grisvard, C., & Léonard, F. (1985). Intermediate cognitive organizations in the process of learning a mathematical concept: The order of positive decimal numbers. *Cognition and Instruction, 2*, 157-174.

Schneider, M., & Siegler, R. S. (2010). Representations of the magnitudes of fractions. *Journal of Experimental Psychology: Human Perception and Performance, 36,* 1227–1238. doi: 10.1037/a00181701227

Siegler, R. S., Thompson, C. A., & Schneider, M. (2011). An integrated theory of whole number and fractions development. *Cognitive Psychology, 62,* 273–296. doi:10.1016/j.cogpsych.2011.03.001

Siegler, R. S., Duncan, G. J., Davis_Kean, P. E., Duckworth, K., Claessens, A., Engel, M., Susperreguy, M. I., & Chen, M. (2012). Early predictors of high school mathematics achievement. *Psychological Science, 23,* 691–697. doi: 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 Science, 17,* 13–19. doi: 10.1111/desc.12155

Siegler, R. S. & Pyke, A. A. (2013). Developmental and individual differences in understanding of fractions. *Developmental Psychology, 49*, 1994–2004. doi: 10.1037/a0031200

Siegler, R. S., & Lortie–Forgues, H. (2014). An integrative theory of numerical development. *Child Development Perspectives, 8*, 144–150. doi: 10.1111/cdep.12077

Sprute, L., & Temple, E. (2011). Representations of fractions: Evidence for accessing the whole magnitude in adults. *Mind, Brain, and Education, 5,* 42–47. doi: 10.1111/j.1751-228X.2011.01109.x

Stern, E. (1993). What makes certain arithmetic word problems involving the comparison of sets so difficult for children? *Journal of Educational Psychology, 85,* 7–23. doi:10.1037/0022-0663.85.1.7

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. Doi: 10.1016/S0028-3932(98)00158-4

Szucs, D., & Soltesz, F. (2007). Event-related potentials dissociate facilitation and interference effects in the numerical Stroop paradigm. Neuropsychologia, 45, 3190-3202. doi: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, 37A*, 571–590. doi: 10.1080/14640748508400920

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. doi : 10.1037/0278-7393.17.4.681

Tipper, S. P. (2001). Does negative priming reflect inhibitory mechanisms? A review and integration of conflicting views. *The Quarterly Journal of Experimental Psychology*, *54A*, 321–343. doi:10.1080/713755969

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. doi: 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. Doi: 10.1016/j.pscychresns.2009.07.005

Vamvakoussi, X., & Vosniadou, S. (2012). Bridging the gap between the dense and the discrete: the number line and the “rubber line” bridging analogy. *Mathematical Thinking and Learning, 14,* 265–284. doi: 10.1080/10986065.2012.717378

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. doi:10.1016/j.jmathb.2012.02.001

Vamvakoussi, X. (2015). The development of rational number knowledge: Old topic, new insights. *Learning and Instruction, 37,* 50–55. doi: 10.1016/j.learninstruc.2015.01.002

Van Dooren, W., Lehtinen, E., & Verschaffel, L. (2015). Unraveling the gap between natural and rational numbers. *Learning and Instruction, 37,* 1–4. doi: 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. doi: 10.1080/14794802.2013.797747

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: Erlbaum.

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: Routledge.

Vosniadou, S., & Skopeliti, I. (2013). Conceptual change from the framework theory side of the fence. *Science and Education,* 1–19. doi: 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. Doi: 10.1016/j.neuroimage.2005.10.015

Zhang, L., Fang, Q., Gabriel, F., & Szücs, D. (2014). The componential processing of fractions in adults and children: effects of stimuli variability and contextual interference. *Frontiers in Psychology, 5*: 911. doi: 10.3389/fpsyg.2014.00981