The relationship between primary school children's inhibition and the processing of rational numbers

Karen De Keersmaeker[1], Jo Van Hoof[2], and Wim Van Dooren

[1]Centre for Instructional Psychology and Technology, KU Leuven

[2] Department of Teacher Education, University of Turku

Author Note

Karen De Keersmaeker https://orcid.org/0000-0002-3755-5910

Jo Van Hoof https://orcid.org/0000-0003-4752-6221

Wim Van Dooren https://orcid.org/0000-0001-5002-4340

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Correspondence concerning the article should be addressed to Karen De Keersmaeker, Dekenstraat 2, box 3773, 3000 Leuven, Belgium. Email: karen.dekeersmaeker@kuleuven.be

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Abstract

Processing rational numbers is difficult for many children. The natural number bias is one possible explanation for why children struggle with rational numbers. It refers to the tendency to overgeneralise the properties of natural numbers. In this study it is argued that in order to be successful in rational number tasks, individuals need to inhibit or suppress their unwanted impulses (in this case the tendency to apply natural number properties). It was investigated whether inhibition plays a role in the occurrence of the natural number bias among primary school children by administering two rational number tasks, two Stroop tasks and a questionary measuring inhibitory skills. The results indicated that primary school children were hampered by the natural number bias both in terms of accuracy rates and response times. Additionally, the results did not yield strong evidence for a relationship between inhibition and the occurrence of the natural number bias.

Keywords

inhibition; inhibitory control; rational numbers; natural number bias

Introduction

For decades, studies have shown the struggle of primary school children when processing rational numbers. For example, children find it difficult to identify the largest decimal in a set (Resnick et al., 1989; Sackur-Grisvard & Léonard, 1985), or explain why a fraction contains two numbers (Smith et al., 2005). It is important to further examine these difficulties since fraction knowledge of primary school children predicts later mathematics achievement in high school (Siegler et al. 2012). One of the explanations frequently raised for these difficulties is the *natural number bias*, or the tendency to overgeneralise the properties of natural numbers, which results in the application of these properties in rational number tasks in cases where this is inappropriate (Ni & Zhou, 2005; Smith et al., 2005). The origins of this bias are still a matter of debate (Ni & Zhou, 2005), yet a possible explanation can be found in the culturally privileged character of natural numbers (Gelman, 2000). Based upon early experiences with natural number (e.g., counting songs or board games) and the considerable emphasis placed on natural numbers during the first years of formal instruction, children create an idea of how numbers behave based on the properties of natural numbers (Gelman, 2000; Greer 2004). This can result in errors since the properties between natural and rational numbers may differ (Van Hoof et al., 2017c).

An example of a difference between rational and natural numbers can be found in the way one can determine their size. Longer numbers are often believed to be larger, which is true for natural numbers but not always for rational numbers (e.g., 65 is larger than 8, but 0.65 is not larger than 0.8).;Concerning fractions, children frequently perceive the numerator and the denominator as two separate numbers and fail to take into account the ratio between them, which may lead to the incorrect idea that when the value of the numerator, the denominator or both increases; the total numerical value of a fraction increases as well (Durkin & Rittle-Johnson, 2015; Meert et al., 2010; Smith et al., 2005; Van Hoof et al., 2013). Previous research documented that higher accuracy rates and/or faster reaction times are attained on items where applying the properties of natural numbers lead to a correct answer on rational number tasks too (called congruent items) compared to items where applying the natural number properties would result in an incorrect answer (called incongruent items) (e.g., Van Hoof et al., 2021). Furthermore, this bias (either in accuracy rates or in reaction times) arises among primary school children (Van Hoof et al., 2015b),secondary school students (Van Hoof et al., 2013), adults (DeWolf & Vosniadou, 2014; Vamvakoussi et al., 2012), and even mathematicians (Obersteiner et al., 2013). Besides a difference in size, natural and rational numbers also differ in terms of operations (e.g., Multiplication makes bigger for natural numbers but not necessarily for rational numbers), and density (e.g., There is always a finite number of natural numbers between two natural numbers, while there are infinitely many between two rational numbers; Van Dooren et al., 2015). This study focuses on size since research has indicated the importance for this property in young children's development of rational number understanding (Van Hoof et al., 2015b).

Theoretical frameworks

Two theoretical frameworks which can be seen as complementary perspectives through which to view this bias are frequently used to explain why individuals show a natural number bias.

The framework theory approach to conceptual change

This first theory starts from the assumption that learners structure knowledge and experiences in order to make sense of the world. These frameworks represent "a relatively coherent and principle-based system, which is generative in that it allows children to make predictions and explanations and deal with unfamiliar problems" (Vamvakoussi & Vosniadou, 2010, p.185). When learners are confronted with new experiences or knowledge, they try to fit these new insights into the already existing frameworks in their minds (Vamvakoussi & Vosniadou, 2010). The process is almost effortless when new information is in line with the already existing framework, and new information is merely added. In contrast, when the new knowledge is incompatible with the frameworks that learners already built, the prior understanding of the learner is in conflict with the newly presented knowledge and conceptual change is needed, i.e. this prior knowledge needs to be revised (Merenluoto & Lehtinen, 2004; Vosniadou, 1994; Vosniadou et al., 2008). This is a challenging and time-consuming process since existing frameworks are often based on implicit assumptions of which the learner is unaware, and that are often given up only partially (Van Hoof et al., 2017a; Vamvakoussi & Vosniadou, 2010; Vosnadou, 1994).

Applied to the natural number bias, this theory assumes that learners experience difficulties with rational numbers because of their extensive earlier encounters with natural numbers, which are used to create a coherent framework with implicit ideas of how numbers behave. Due to the differences between natural and rational numbers, this framework may be incorrect when working with rational numbers. As a result, learners need to undergo conceptual change, the initial structure of their mental framework has to be restructured (Vamvakoussi & Vosniadou, 2010; Vosniadou et al., 2008). As learners start from a naïve idea of how rational numbers behave (based on natural number knowledge), and move towards the correct idea of how rational numbers behave it is not uncommon for them to reach intermediate states of understanding, where they try to combine the initial number knowledge with the correct number knowledge. An example of a naïve concept is thinking that longer decimals are always larger. This idea is based upon natural number knowledge (e.g., Longer natural numbers are always bigger; González-Forte et al., 2020; Van Hoof et al., 2017a; Vamvakoussi & Vosniadou, 2010; Vosnadou, 1994). Although most studies have attributed this error to a natural number bias, Roell et al., (2019a) found evidence that this error could also partially be explained by a visuospatial bias due to the interference between the magnitude of the numbers to be compared and their physical length. In an intermediate state of understanding the learner could for example show a reversed bias and think in the opposite way, that longer decimals are smaller (González-Forte, 2020; Van Hoof et al., 2017a; Vamvakoussi & Vosniadou, 2010; Vosniadou, 1994).

The dual process theory

The framework theory to conceptual change does not explain why people do not succeed in certain tasks when they have internalised all the necessary knowledge and skills to complete these tasks successfully. Since about a decade, scholars have acknowledged the possibility that the new, correct knowledge and the incompatible prior knowledge may co-exist, and influence learners' performance. This is where the dual process theory comes into play (Gillard et al., 2009). This theory assumes the existence of two types of cognitive processes: heuristic processes (which are unconscious, fast and automatic, also called intuitive), and analytical processes (which are slow and controlled) (Gillard et al., 2009; Evans, 2008). Since heuristic reasoning does not always lead to a correct answer, the interference of analytical reasoning may be required to correctly solve a task. When this analytical reasoning is necessary, there are two possibilities: Firstly, analytic reasoning does not interfere and a rather quick, though incorrect answer in line with the heuristic reasoning will be given. Secondly, analytical reasoning will interfere with heuristic reasoning. The analytical processing will evaluate the correctness of the answer obtained by heuristic reasoning, tries to inhibit a possible incorrect answer, and attempts to develop a correct answer; a process being more time consuming (De Neys et al., 2010; Evans, 2008; Gillard et al., 2009; Van Hoof et al., 2013; Van Hoof et al., 2017c). Hence, according to the dual process theory, incorrect answers are generated when heuristic reasoning is not enough to generate a correct answer and the interference of analytic reasoning is absent or when the interference of analytical reasoning is not successful (Gillard et al., 2009; Van Hoof et al., 2017c).

The dual process theory is an overall theory of how the human mind works and can be applied to various mathematical topics, such as the natural number bias (Gillard et al., 2009; Houdé & Guichart, 2001). Here, it is assumed that learners first encounter natural numbers and, therefore, knowledge on how natural numbers behave is first acquired and the most automatized knowledge. Researchers thus assume that knowledge of natural numbers is heuristic in nature. Since rational number knowledge is achieved at a later age, it is assumed to be less deeply acquired than natural number knowledge and thus based on analytical reasoning (De Neys et al., 2010; Gillard et al., 2009; Van Hoof et al., 2017c). Consequently, more time is needed to solve incongruent items (since natural number knowledge needs to be inhibited) compared to congruent items (where inhibition of natural number knowledge is not necessary; Van Hoof et al., 2021). Several studies have indicated that secondary school children, adolescents, and even experienced mathematicians indeed need more time to correctly solve incongruent items compared to congruent items when processing rational numbers (Obersteiner et al., 2013; Vamvakoussi et al., 2012; Van Hoof et al., 2013). Therefore it could be interesting to examine if inhibitory control has an influence on the occurrence of the natural number bias.

Inhibition

In tasks where natural number bias related errors are made, it is assumed that individuals use their knowledge of natural numbers to make sense of rational numbers (e.g., Ni & Zhou, 2005). Here, suppressing natural number knowledge is necessary to obtain a correct response, which in line with prior research described in the previous paragraph is described as heuristic in nature (Christou, 2015). Hence, inhibition, one's ability to control "attention, behaviour, thoughts and/or emotions to override a strong internal predisposition or external lure" (Diamond, 2013, p.136), will be the focus of the study.

Previous research has indicated that seventh graders, adolescents and adults need inhibitory control to correctly solve incongruent fractions and decimals (Fu et al., 2020; Roell et al., 2019b; Rossi et al., 2019; Van Hoof et al., 2021). However, one can assume that the necessary fraction and decimal knowledge is already well established in adults, while this is not yet the case in primary school children. Moreover, given that inhibition is difficult for young children and still matures during adolescence (Diamond, 2014; Luna, 2009), the relationship between inhibition and rational number processing could be more pronounced in this younger age group compared to seventh graders and adolescents. To our knowledge, only two studies have investigated the relationship between inhibitory skills and the occurrence of the natural number bias in primary school children. First, Avgerinou and Tolmie (2020) investigated the association between inhibition and the natural number bias in 8- to 10-year-olds, and concluded that lower performance on a non-numerical Stroop task leads to longer response times when correctly solving incongruent items in a fraction and decimal comparison tasks, but only under conditions of high cognitive load. Second, Gómez et al., (2015) found that reaction times as measured by a numerical Stroop task predicted accuracy scores of incongruent items in a fraction comparison task.

However, there may be some limitations with these studies. First, both studies did not control for *benchmarking* or *gap thinking.* Benchmarking refers to using reference points (e.g., 1/2) to make it easier to compare different fractions (Obersteiner et al., 2020). Items are easier when one of the fractions is below 1/2 and the other one is above 1/2, for instance, or when one fraction is very close to 1 while the other is clearly not. Gap thinking refers to a reasoning on the difference between the numerator and the denominator: the difference between the numerator and denominator of each fraction is being compared and the fraction with the smallest difference (or gap) is seen as the largest fraction (Obersteiner et al., 2013). Gap thinking is a commonly used, and essentially an incorrect strategy, that in many cases may still lead to the correct solution (González-Forte et al., 2020). In the studies of Gómez et al. (2015) and Avgerinou and Tolmie (2020), the use of benchmarking and gap thinking cannot be excluded, and engaging in these strategies could affect the results. Therefore, it is valuable to use an item set that is controlled for these two approaches.

Secondly, as far as we know both studies first investigated if the children in their sample showed signs of a natural number bias by only looking at the general scores of the children. By concluding that the overall group of children is hindered by the natural number bias, the authors used this full sample to investigate if scores on the natural number bias are related to inhibitory skills. However, it is possible that some children show signs of a *reversed natural number bias*, and that this phenomenon is not seen when only looking at the performances of the overall group. Children who attain a better score on incongruent items due to their intermediate state of understanding in the conceptual change process, know that rational and natural numbers behave differently, but fail to really understand how rational numbers behave, resulting in answering in the opposite way than one would see if they had a natural number bias (e.g., A child thinks 4/7 is smaller than 3/4 as 4 is larger than 3 and 7 is larger than 4; Reinhold et al., 2020). A child with a reversed bias answers incongruent items more correctly and/or needs less time to correctly answer incongruent items compared to congruent items. Inhibition may here play a role since children need to supress their initial reasoning to correctly answer congruent items.

It is possible that the studies of Avgerinou & Tolmie (2020), and Gómez et al., (2015) found a relationship between inhibitory skills and the natural number bias due to not controlling for benchmarking and gap thinking, or not excluding children with a reversed natural number bias. In this study, we tried to further examine the relationship between inhibition and the natural number bias by first designing an item set that controlled for the distance effect (Meert et al., 2010), benchmarking and gap thinking, and second by excluding children who show signs of a reversed natural number bias, in order to deliver stronger evidence for the relationship between inhibition and the natural number bias.

The present study

The first part of the study examines if the primary school children in our sample show signs of the natural number bias when comparing fractions or decimals. Based on previous research, we hypothesize that this bias will manifest itself in terms of lower accuracy rates on incongruent items and/or longer response times on correctly solved incongruent items compared to congruent items, both for fractions and for decimals (e.g., Obersteiner et al., 2013; Van Hoof et al., 2015b). This leads us to the first research question: Do primary school children show signs of the natural number bias in terms of accuracy rates and/or reaction times when comparing the size of fractions and the size of decimals? The second part of this study examines the role of inhibition in processing rational numbers. As argued before, learners may need to inhibit their heuristic knowledge (based on properties of natural numbers) in order to generate a correct answer to incongruent rational number tasks (Christou et al., 2015; Gómez et al., 2015; Van Hoof et al., 2017c). Therefore it is interesting to investigate if inhibition plays a role in the occurrence of the natural number bias. This leads to the second research question: Is there a relationship between inhibitory skills of primary school children and the presence of the natural number bias? We hypothesize that children who have stronger inhibitory skills will show less traces of the natural number bias.

Methods

Participants

A total number of 70 children (31 boys, 39 girls) coming from three schools in [blinded] participated in this study. Data was collected from fifth graders (M_{age} =10.11), who already received one year instruction on both decimals and fractions, since it is important that the participants have a certain amount of knowledge about rational numbers, and to assure that no ceiling effects on the rational number tasks occurred since this could distort the results. The data was collected according to the ethical guidelines of [Blinded], and all parents signed an informed consent.

Procedure

All participants engaged in a fraction comparison task, a decimal comparison task, a numerical Stroop task, a non-numerical Stroop task, and a reaction time test, all created in OpenSesame. The instruction was given to work as accurate and as fast as possible. The participants received three practice trials before the beginning of each task, feedback was given when the practice trials were answered incorrectly. For each task, half of the correct answers were presented on the left side of the screen, while the other half was presented on the right side. The children had to indicate the correct answer by pressing 'd' (if left was correct), or 'k' (if right was correct) on the keyboard. Additionally, teachers were asked to fill out a questionnaire about the inhibitory skills of the participating children.

Instruments

Rational number knowledge

The fraction comparison task was based on previous research of Obersteiner et al., (2013), and had two different types of fractions: fractions with common components (fraction CC task) and without common components (fraction WCC task). Additionally, each of these types of fractions had both congruent and incongruent items. In the fraction CC task, congruent items are fractions with common denominators (e.g., 2/5 and 1/5); incongruent items are fractions with common numerators (e.g., 1/3 and 1/8). In the fraction WCC task, congruent items are items where the largest fraction has also the largest numerator and the largest denominator (e.g., 4/9 and 3/7); incongruent items are items where the numerical larger fraction is the fraction with the smallest numerator and the smallest denominator (e.g., 1/3 or 2/7). The test contained 48 items, 12 fractions in each condition. The item set was controlled for benchmarking to 0, 1/2, and 1 by not using fractions smaller than 0.1, fractions bigger than 0.9, and by using 12 fraction pairs with both fractions below 0.5 and 12 pairs with both fractions above 0.5. Additionally, the item set was controlled for the distance effect by assuring that the mean distance between the congruent and incongruent items was equal. A Mann-Whitney test indicated that the mean distance between congruent and incongruent items was the same for the fraction CC task ($U = 43.00$, $p = 0.92$) and the fraction WCC task ($U = 68.00$, $p = .843$). Moreover, the item set controlled for gap thinking where possible. Half of the items in the congruent condition of the fraction WCC task controlled for this phenomenon. It is mathematically impossible to control for gap thinking in the incongruent condition or in the fraction CC task. Lastly, all of the used fractions were proper and irreducible.

The decimal comparison task contained 24 congruent (where a longer decimal is the larger decimal e.g., 0.218 and 0.19) and 24 incongruent items (where the longer decimal is the smaller decimal e.g., 0.42 or 0.392) (e.g., Van Hoof et al., 2015a)., and controlled for benchmarking at 0 and ½, in the same way as in the fraction task, and for the distance effect, the mean distance between the congruent and incongruent items was the same ($U = 275$, $p = 0.788$).

Inhibition

Inhibition was measured by a numerical and non-numerical Stroop task and the BRIEF-2 (e.g., Bellon et al., 2016). In the numerical Stroop task, children were asked to indicate the physically biggest number. The task included 20 items, whereof half congruent (where the physical biggest number also had the biggest numerical value) and half incongruent (where the physical bigger number had the lowest numerical value). The physically bigger items were three times bigger compared to the physically smaller items.

In the non-numerical Stroop task, children had to indicate the physically biggest animal out of two animals. The test contained 10 congruent items where the physical biggest animal is also the biggest animal in real life (e.g., The comparison of a caterpillar and a camel, when the camel is physically represented bigger), and 10 incongruent items where the physically biggest animal is the smallest animal in real life (e.g., The comparison of a rhino with a ladybug, when the ladybug was physically represented as the biggest animal).

The *Behaviour Rating Inventory of Executive Function-2* (or BRIEF-2) is a standardised questionnaire that measures the executive functions of 5 to 18 year olds. The test is divided into eight subareas of executive functioning of which inhibition is one (Huizinga & Smidts, 2020). For this study, the teachers were asked to fill out the items concerning inhibition (8 items), in which the teacher is confronted with different behaviours that children could pose (e.g., The child acts without thinking), and has to indicate to what extent the child has exposed this behaviour during the last six months, on a three point scale (never – sometimes – always) (Huizinga & Smidts, 2020). It can be assumed that the BRIEF-2 and Stroop tasks capture different aspects of inhibition since they are not correlated (Bellon et al., 2016).

Reaction time

This study controlled for reaction time since it was considered as both in the dependent variables and in several inhibition measures, that speed of responding plays a major role. The reaction time test was re-used from a previous study of Bellon et al. (2016) containing 20 items in which children have to indicate the colored figure out of two figures.

Data analysis

In order to answer our first research question a GEE (generalized Estimating of Equations) was used in order to take into account the possible within-subject correlations across the various items (Liang & Zeger, 1986). Due to its dichotomous nature, the accuracy rates were analysed by a binary logistic regression, whereas the continuous response times were analysed by a linear regression (e.g., Van Hoof et al., 2013).

In order to answer our second research question, correlational and multiple hierarchical linear regressions were conducted. First, a new variable was created as a measure of the natural number bias (mean accuracy incongruent items / mean accuracy congruent items) for each of the rational number tasks. This variable represents how many times less incongruent items are answered correctly compared to congruent items. To create a measure of learners' inhibition skills, the same operation (accuracy incongruent/ accuracy congruent) was repeated for the Stroop tasks. Additionally, in order to include the reaction time data in the analyses, a new variable was created that represents how much more time was needed to correctly solve an incongruent item compared to a congruent item (median reaction time correctly solved incongruent items / median reaction time of correctly solved congruent items) for each rational number task (as a measure of the natural number bias) and the Stroop tasks (as a measure of learners' inhibition). This leads to the following newly created variables: three natural number bias accuracy scores (fractions CC, fractions WCC, decimals), three natural number bias reaction time scores (fractions CC, fractions WCC, decimals), two inhibition accuracy scores (numerical and non-numerical Stroop task) and two inhibition reaction time scores (numerical and non-numerical Stroop task). It is important to note that the creation of these new variables may result in negative relations between inhibition measures and the natural number bias. For instance, a child who is hindered by the natural number bias in terms of accuracy and has lower inhibitory skills in terms of reaction time, would receive a natural number bias accuracy score below 1 and inhibition reaction time score above 1, resulting in a negative relationship.

Results

Outliers were identified as participants who did not understand the Stroop or rational number tasks (e.g., Participants scoring below 50% on both conditions in a certain task), and as items with response times that deviated more than three standard deviations from the mean of each task and congruency per participant, and lastly, extremely low reaction times (below 500 ms for the rational number tasks and 250 ms for the Stroop tasks). Ceiling effects were found for accuracy rates on the Stroop tasks, in both the congruent and incongruent condition (see Table 1). Remarkably, participants attained a higher mean reaction time in the reaction time task compared to the Stroop tasks. The reaction time task was the first task for the participants, whereas the experiment always ended with two Stroop tasks. Since the operation (pressing ‘d’ or pressing ‘k’) was the same for all tasks, it may be that learning effects have occurred, which could explain this finding.

The natural number bias

In a first step, it was analysed whether the primary school children showed signs of the natural number bias (in terms of the accuracy and/or response time on a given item). In a second step – if a natural number bias could be found- it was investigated whether the strength of this natural number bias was equally large in all three rational number tasks.

Accuracy rates

Across all task types, analyses revealed a significant main effect of congruence, indicating that children answered congruent items (M = 82%, SD = .39) more accurately than incongruent items (M = 61%, SD =.49), χ^2 (1, N = 6456) = 82.70, $p < .001$. There was a significant main effect of task, χ^2 (2, N = 6456) = 173.71, $p < .001$. On average children answered 77% correctly on the decimal task, 73% in the fraction CC task, and 59% in the fraction WCC task. Further, a significant interaction effect between item and task was found, χ^2 (2, N = 6456) = 77.32, $p <.001$, the natural number bias was not equally strong among the three different rational number tasks. The pairwise comparison indicated that congruent items were answered more correctly compared to incongruent items for each of the three rational number tasks (see Table 2). According to the odds ratios, the bias was the weakest in the fraction WCC task (OR = 1.34, 95 % CI [1.10, 1.63]), stronger in the decimal task (OR = 3.78, 95% CI [3.15, 4.53]), and the strongest in the fraction CC task (OR = 6.36, 95% CI [4.89, 8.27]).

Reaction times

Next, the reaction times of the correctly answered congruent items were being compared to reaction times of the correctly solved incongruent items (See Table 3). Since the GEE including an interaction effect between congruency and task was unable to achieve convergence, a GEE including only a main effect of congruency was conducted for each task separately. Children did not need more time to correctly solve incongruent items (*M* = 1802.15ms, *SD* = 931.87) compared to congruent items (*M* = 155.96ms, *SD* = 840.47) in the decimal task χ^2 (1, *N* = 2470) = 1,62, *p* =.203. A main effect of congruence was found for the fraction CC task, χ^2 (1, *N* = 1159) = 5.45, *p* =.02, indicating that children had longer reaction times in order to solve the incongruent items correctly (*M* =3868.40ms, *SD* = 3681.35) compared to the congruent items (*M* = 2309.07ms, *SD* =1432.28). Finally, a main effect of congruence was found for the fraction WCC task, χ^2 (1, *N* = 959) = 6.12, *p* <.013. Children needed more time to solve incongruent items (*M* = 4824.68ms, *SD* = 5040.43) correctly compared to congruent items (*M* = 4300.94ms, *SD* = 6129.22). According to the Cohen's *d* effect size, the natural number bias was the strongest in the fraction CC task (*d* = 0.49) , and the weakest in the fraction WCC task (*d* = 0.09).

Inhibition and the natural number bias

Correlational and multiple hierarchical linear regressions were conducted in order to examine the relationship between inhibition and the natural number bias. Scores below or higher than three standard deviations of their mean score were eliminated, together with children who show a reversed natural number bias (i.e. scoring above 1.05 on the natural number bias accuracy score or scoring below .95 on the natural number bias reaction time score for each rational number task). The correlation matrix can be found in Table 4. Since a lot of the children showed signs of a reversed bias, it was chosen to work with a pairwise deletion. The number of students ranged between 35 to 64 for this analysis. The number of participants ranged from 22 to 61 for each linear regression (concrete numbers can be found in the regression tables). The different assumptions of regression were tested before conducting the different linear regressions. All VIF's were below 1.5, the assumption of homoscedasticity was not met for the natural number bias accuracy score on the decimal task. Consequently, these results should be interpretated carefully.

Inhibition and the accuracy rates

Multiple hierarchical regressions were conducted to investigate the relationship between inhibition and accuracy rates on each of the three rational number tasks. Five variables were used to measure inhibition: the BRIEF-2, two inhibition accuracy scores, and two inhibition reaction time scores. The variable that correlated the most with the corresponding depending variable was entered first in each analysis. Bayesian Factors were calculated for each predictor separately. Concerning the decimal task, the BRIEF-2 was found to be a significant predictor. Including this variable explained 7.3% of the additional variance (p = .040) (see Table 5). The results indicated no significant relationship between any other measure of inhibition and the natural number bias accuracy score on the fraction tasks (see Table 6, and 7).

Inhibition and reaction times

Correlational and hierarchical regressions were conducted to further investigate the relationship between inhibition and the reaction time score on each rational number task. Given the young age of the children, we expected to find traces of the natural number bias in many children. Therefore we did not exclude children who performed below chance. It could be argued that children performing below chance-level did not understood the rational number tasks, especially given the low accuracy rates on the fraction WCC task. However, we have strong reasons to believe that the children did understand the fraction WCC task. First, we included fifth graders, who already received a year instruction on rational numbers, and administered only fractions containing numerators and denominators below 11. Second, children received three practice trails at the start of each task, and received feedback when solving the trials incorrectly. Third, the instruction of the fraction WCC task was identical to the instruction of the fraction CC task, where the accuracy rates were well above chance. Although it thus seems unlikely that children did not understand the fraction WCC task, it is advised to still interpret the results carefully as the accuracy rates were rather low. The same five inhibition measures were used as for the accuracy scores. In each model, we controlled first for reaction time, followed by the variable that correlated the most with the corresponding depending variable. Bayesian Factors were again calculated. The results indicated no significant relationship between any measure of inhibition and the natural number bias reaction time score on any of the rational number tasks (see Table 8, 9, and 10).

Discussion

Our study extended previous research by controlling for the benchmarking and gap thinking, and by eliminating children with a reversed natural number bias. Our results confirmed that primary school children show signs of a natural number bias both in terms of accuracy rates and/or reaction times. The score on the BRIEF-2 is a significant predictor for the natural number bias accuracy score on the decimal task. The assumption of homoscedasticity was not met for this linear regression, thus this finding should be interpretated carefully. These results do not confirm the results of Fu et al. (2020), Roell et al. (2019b), Rossi et al. (2019), and Van Hoof et al. (2021), who found clear evidence that 7th graders, adolescents, and adults need to inhibit their natural number knowledge in order to correctly solve the incongruent fractions and decimals. The results also contradict the findings of Gómez and colleagues (2015), as we did not find reaction times on the numerical Stroop task predicted accuracy rates when comparing incongruent fractions. This could be due to many possible reasons, which we will discuss below.

First, although it is necessary to eliminate children with a reversed natural number bias, this led to a small number of participants in some regressions. Therefore the lack of statistical power may have hindered findings of significant relationships, as the post hoc power analyses indicated poor statistical power for all regressions (see Tables 5 – 10).

Second, the correlational approach used in this study differs from the previously used experimental approaches such as the negative priming paradigm Fu et al., 2020; Roell et al., 2019b; Rossi et al., 2019) or the strategy switch cost approach (Van Hoof et al., 2021). Moreover, different measures of inhibition were used.

Third, the used inhibition tasks can explain conflicting findings. For instance: Although the subscales of the BRIEF-2 are reliable (Huizinga & Smidts, 2020), it is possible that subscale was too limited to measure small differences in inhibition between participants (Bellon et al., 2016). Similarly, despite the well-established replicable experimental effects of the Stroop tasks, these tasks may be less suited to investigate individual differences, especially given the high accuracy rates on the Stroop tasks. This can be explained by the different meanings of reliability being hold by the two approaches. While correlational approaches are interested in between-subject variance, experimental approaches search for within-subject variance, thus from a correlational approach, a reliable instrument is able to rank individuals, whereas from an experimental approach the reliability is defined by the ability to replicate effects (Hedge et al., 2018). Additionally, while inhibiting the numerical value or the real-size of the animals is more in line with the inhibition necessary in the fraction tasks, inhibiting the physical size of numbers and animals is more in line with the inhibition necessary in the decimal comparison task. In sum, administering different inhibition tasks (e.g., different types of Stroop tasks, flanker task, go/no-go task, stop-signal task) could lead to different results.

Fourth, in previous research, a relationship between inhibition and the natural number bias was found among older children (e.g., Fu et al., 2020; Roell et al., 2019b; Rossi et al., 2019; Van Hoof et al., 2021), while we fail to find this relationship in younger children. It could be possible that the children in our study are not yet aware of their primary intuitions, which explains the absence of a clear relationship between inhibition and the presence of the natural number bias: there are no responses being inhibited. A new study including a longitudinal approach could be interesting to investigate at which specific time point inhibition starts to play a role.

Fifth, the results of Avgerinou & Tolmie (2020) provided evidence that when comparing incongruent fractions and decimals, inhibition was only important in primary school children when high levels of cognitive demand were placed on the learner. The possible lack of cognitive demand in our task could explain the absence of a correlation between inhibition and the natural number bias.

Lastly, it might be that the relationship between inhibition and the presence of the natural number bias can only be observed by children with an atypical development of inhibition (e.g. ADHD or dyscalculia; Bellon et al., 2016). For instance, Van Hoof et al. (2017b) suggest that learners with dyscalculia performed lower on rational number tasks compared to their peers. Moreover, this difference in performance was larger on tasks where inhibiting rational number knowledge was necessary to generate a correct answer. A new study could compare if the strength of the relationship between inhibition and the natural number bias is the same for typically developing school children and children with an atypical development of inhibition.

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Table 1

Mean Accuracies and Reaction Times per Task

Task	Congruency	Accuracy		Response time (ms)	
		M	SD	M	SD
Decimals		.77	.423	1542.11	894.839
	Congruent	.88	.330	1526.41	845.675
	Incongruent	.66	.475	1557.74	933.117
Fraction CC		.73	.446	2727.12	2672.996
	Congruent	.89	.310	2307.80	1494.373
	Incongruent	.56	.496	3142.24	3416.087
Fraction WCC		.59	.493	4064.64	5002.800
	Congruent	.62	.485	4230.49	5516.803
	Incongruent	.55	.498	3898.99	4427.536
Numerical Stroop		.95	.213	747.51	602.380
	Congruent	.97	.177	716.86	531.338
	Incongruent	.94	.244	778.30	665.130
Non-numerical Stroop		.97	.157	678.01	408.753
	Congruent	.98	.138	639.04	320.613
	Incongruent	.97	.174	716.87	477.906
Reaction time		.92	.275	864.96	780.419

Table 2

Pairwise Comparison per Congruency Grouped by Task

(I) task* congruency	(J) task*item	Mean difference (I-J)	SD	df	Sig.	95% Wald CI for diff.	
						Under	Upper
Decimal*CO	Decimal*IC	.34	.041	1	<.001	.26	.42
Frac CC*CO	Frac CC*IC	.43	.040	1	<.001	.36	.51
Frac WCC*CO	Frac WCC*IC	.26	.050	1	<.001	.16	.35

Note. Frac = Fractions

Table 3

Mean Reaction Times Correctly Solved Items

Task	Item	M (in ms)	SD
Decimals		1661.81	889.142
	Congruent	1555.96	840.467
	Incongruent	1802.15	931.871
Fractions CC		2838.03	2637.902
	Congruent	2309.07	1432.283
	Incongruent	3868.40	3681.347
Fractions WCC		4546.15	5648.833
	Congruent	4300.94	6129.216
	Incongruent	4824.68	5040.433
Numerical Stroop		726.75	527.847
	Congruent	708.20	494.140
	Incongruent	746.00	560.429
Non-numerical Stroop		671.89	401.578
	Congruent	638.13	317.831
	Incongruent	705.95	469.043
Reaction time		819.41	607.618

Table 4

Correlation Matrix Inhibition and the Natural Number Bias

	1.	2.	3.	4.	5.	5.	7.	8.	9.	10.	11.	12.
1. Reaction time	-											
2. Non-numerical Stroop (acc)	-.004	-										
3. Non-numerical Stroop (RT)	-.051	.038	-									
4. Numerical Stroop (acc)	-.116	-.171	.018	-								
5. Numerical Stroop (RT)	.347	-.102	.279*	.091	-							
6. BRIEF-2	.088	.094	.060	.178	-.025	-						
7. Decimals (acc)	.417**	-.008	-.129	.111	.226	.143	-					
8. Fractions CC (acc)	-.123	.082	-.119	.125	-.014	-.102	.080	-				
9. Fractions WCC (acc)	-.305*	.180	-.130	-.236	-.171	-.014	.030	.585**	-			
10. Decimals (RT)	-.349*	-.211	-.204	.195	-.006	-.002	-.186	-.102	.251	-		
11. Fractions CC (RT)	.021	-.276	.090	.138	.134	-.281*	-.013	.001	-.143	.163	-	
12. Fractions WCC (RT)	.229	.189	-.036	-.111	-.084	-.163	-.019	-.133	-.162	-.211	.197	-

Note. acc = accuracy, RT = reaction time, **correlation is significant at the at the 0.01 level (2-tailed), *correlation is significant at the 0.05 level (2-tailed).

Table 5

Inhibition and Accuracy Rates on the Decimal Task (n = 58, power = .69)

	R	R Square	Adjusted R Square	Std. Error of the Estimate	Change Statistics					BF10
					R Square Change	F Change	df1	df2	Sig. F Change	
BRIEF-2	.271	.073	.057	.43718	.073	4.434	1	56	.040	0.617
Numerical Stroop (acc)	.316	.100	.067	.43475	.027	1.629	1	55	.207	0.636
Numerical Stroop (RT)	.380	.144	.097	.42778	.044	2.805	1	54	.100	0.782
Non-numerical Stroop (RT)	.394	.155	.092	.42906	.011	.679	1	53	.414	0.554
Non-numerical Stroop (acc)	.403	.163	.082	.43129	.007	.454	1	52	.504	0.553

Note. acc = accuracy, RT = reaction time.

Table 6

Inhibition and Accuracy Rates on the Fraction CC Task (n = 32, power = .35)

	R	R Square	Adjusted R Square	Std. Error of the Estimate	Change Statistics					BF10
					R Square Change	F Change	df1	df2	Sig. F Change	
BRIEF-2	.311	.097	.066	.33944	.097	3.206	1	30	.083	0.905
Numerical Stroop (acc)	.355	.126	.065	.33961	.029	.097	1	29	.333	0.543
Non-numerical Stroop (RT)	.371	.126	.065	.33961	.012	.380	1	28	.543	0.566
Numerical Stroop (RT)	.376	.142	.014	.34876	.004	.130	1	27	.721	0.561
Numerical Stroop (acc)	.392	.154	-.009	.35288	.012	.373	1	26	.547	0.659

Note. acc = accuracy, RT = reaction time.

Table 7

Inhibition and Accuracy Rates on the Fraction WCC Task (n = 61, power = . 46)

	R	R Square	Adjusted R Square	Std. Error of the Estimate	Change Statistics					BF10
					R Square Change	F Change	df1	df2	Sig. F Change	
Numerical Stroop (acc)	.236	.056	.40	1.77483	.56	3.485	1	59	.067	0.883
Non-numerical Stroop (acc)	.275	.076	.44	1.77101	.20	1.255	1	58	.267	0.565
Numerical Stroop (RT)	.308	.095	.47	1.76796	.19	1.200	1	57	.278	0.610
Non-Numerical Stroop (RT)	.323	.104	.40	1.77441	.009	.586	1	56	.447	0.566
BRIEF-2	.323	.104	.23	1.79032	.000	.009	1	55	.926	0.486

Note. acc = accuracy, RT = reaction time.

Table 8

Inhibition and Reaction Times on the Decimal Task (n =39, power = .38)

	R	R Square	Adjusted R Square	Std. Error of the Estimate	Change Statistics					BF10
					R Square Change	F Change	df1	df2	Sig. F Change	
Reaction time	.179	.032	.006	.30019	.032	1.224	1	37	.276	0.512
Non-numerical Stroop (RT)	.293	.086	.035	.29571	.054	2.129	1	36	.153	1.210
Numerical Stroop (acc)	.344	.118	.042	.29461	.032	1.269	1	35	.268	0.656
BRIEF-2	.345	.119	.015	.29876	.001	.036	1	34	.850	0.522
Non-numerical Stroop (acc)	.361	.130	-.001	.30128	.011	.432	1	33	.516	0.366
Numerical Stroop (RT)	.386	.149	-.011	.30265	.019	.702	1	32	.408	0.691

Note. RT = reaction time, acc = accuracy.

Table 9

Inhibition and Reaction Times on the Fraction CC Task (n = 22, power = .29)

	R	R Square	Adjusted R Square	Std. Error of the Estimate	Change Statistics					BF10
					R Square Change	F Change	df1	df2	Sig. F Change	
Reaction time	.066	.004	-.045	1.47376	.004	.088	1	20	.769	0.397
Non-numerical Stroop (acc)	.305	.093	-.003	1.44324	.089	1.855	1	19	.189	1.022
BRIEF-2	.402	.162	.022	1.42554	.069	1.475	1	18	.240	0.774
Non-numerical Stroop (RT)	.469	.220	.037	1.41475	.059	1.275	1	17	.274	1.180
Numerical Stroop (RT)	.470	.221	-.022	1.45717	.001	.025	1	16	.877	0.616
Numerical Stroop (acc)	.471	.222	-.090	1.50477	.000	.004	1	15	.952	0.718

Note. acc = accuracy, RT = reaction time.

Table 10

Inhibition and Reaction Times on the Fraction WCC Task (n = 47, power = . 50)

	R	R Square	Adjusted R Square	Std. Error of the Estimate	Change Statistics					BF10
					R Square Change	F Change	df1	df2	Sig. F Change	
Reaction time	.229	.052	.031	.50503	.052	2.482	1	45	.122	0.786
Non-numerical Stroop (acc)	.297	.088	.047	.50093	.036	1.738	1	44	.194	0.704
BRIEF-2	.360	.130	.069	.49512	.041	2.040	1	43	.160	0.881
Numerical Stroop (acc)	.360	.130	.047	.50095	.000	.005	1	42	.943	0.470
Numerical Stroop (RT)	.396	.157	.054	.49900	.027	1.328	1	41	.256	0.698
Non-numerical Stroop (RT)	.398	.158	.032	.50478	.001	.066	1	40	.798	0.576

Note. acc = accuracy, RT = reaction time.