

Research paper

Effects of teaching neuroplasticity on motivation, inhibitory control and task performance, and the role of mindset theory

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ABSTRACT

Background: Frequent and persistent errors resist teaching, partly due to difficulties in mobilizing inhibitory control. A promising strategy to address this challenge involves teaching students about neuroplasticity. Such instruction may indeed foster motivational beliefs (often referred to as *growth mindset*), which in turn could positively influence the mobilization of inhibitory control. This study investigated the effects of a neuroplasticity-based intervention on motivation (including constructs from mindset theory), inhibitory control and task performance.

Method: The final sample included 44 10–12 y/o students recruited from French-speaking elementary schools in the Montreal area (Québec, Canada), primarily through an online advertisement posted on social media. They were assigned to either the experimental group (neuroplasticity intervention) or the control group. They completed a motivational questionnaire at both pretest and posttest and performed a fraction comparison task while undergoing fMRI scanning.

Results: Results indicated that students who learned about neuroplasticity demonstrated significant improvements in motivation and greater activation of the ventrolateral prefrontal cortex (VLPFC), a brain region associated with inhibitory control. However, task performance did not significantly differ between groups. Notably, the change in perceived competence was the only motivational variable significantly associated with brain activity related to inhibitory control.

Conclusions: These findings suggest that teaching neuroplasticity can both foster motivation and neural engagement, with perceived competence emerging as a central variable in this relationship. While the intervention did not produce direct effects on academic performance, it remains a promising cost-effective strategy to support students with inhibitory control difficulties and offers valuable insights for future educational interventions.

1. Introduction

Several studies highlight that one of the major obstacles to student achievement is the difficulty in correcting frequent and persistent errors [1,2]. These errors are often known to be related to the difficulty of resisting some automatisms that can prevail in counterintuitive situations, whereas the appropriate response requires inhibition, i.e. resisting the automatism that leads to an error [3,4]. A well-documented example

is that students tend to say that a third is less than a quarter, since they rely on the automatism "three is less than four" (a bias called the *natural number bias*, see for instance [5–9]). While this automatism is useful and cost-efficient in most situations, in the specific case of fraction comparison it leads students to make a mistake. To overcome the interference caused by the natural number bias, students need to show inhibitory control in order to resist the automatism and allow the "appropriate reasoning" to occur [10,11].

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Inhibitory control-related errors, which go beyond fractions and affect several other areas of academic learning, are known to be particularly persistent and resistant to instruction, making them difficult to correct [1,12]. Indeed, despite having been taught the rule or the “appropriate reasoning” on several occasions, a majority of students regularly continue to commit them [1,12]. One explanation for the difficulty in correcting these errors is that it is not enough for students to *know* the appropriate reasoning to succeed in a counterintuitive situation; they must also succeed in *inhibiting*, i.e. controlling or blocking, the intuitive reasoning (the automatism) leading to an error [3,4]. Indeed, as this automatic or intuitive reasoning is more spontaneous, it tends to manifest itself before the appropriate reasoning, even though students may know or understand this appropriate reasoning. The difficulty to inhibit automatic or intuitive reasoning would therefore explain the persistence of these errors [3,4]. In mathematics particularly, many errors are thought to be due to a difficulty in inhibiting automatisms [13], hence the importance of looking at ways of improving students’ ability to mobilize inhibitory control.

Some studies suggest that a promising strategy for fostering the mobilization of inhibitory control is to teach students how their brain works and learns, by addressing the concept of neuroplasticity [14,15]. This involves explaining to students that it is possible to modify the connections between their neurons, that these connections strengthen and become more effective with effort, practice and the use of appropriate strategies, and that therefore, by practicing resisting automatisms, they will be able to get better at doing so [16]. This type of teaching could promote the mobilization of inhibitory control, possibly through certain motivational beliefs, such as a growth mindset [17]. A growth mindset consists in believing that skills can develop, as opposed to a fixed mindset in which skills are fixed and cannot evolve [17,18]. These motivational beliefs would actually influence the student’s reaction to mistakes: when receiving negative feedback (indicating a mistake), a student with a growth mindset would be more likely to mobilize error-correcting brain mechanisms, particularly those related to inhibitory control, leading to better performance [19–21] and sometimes better academic results [18,22]. Among the studies that have investigated the relationship between teaching the concept of neuroplasticity and academic results, some have, however, obtained divergent results (e.g., [18,23]). A meta-analysis [14] reviewed around ten studies that measured the impact of teaching neuroplasticity on various variables. The interventions were conducted by either a teacher, a research assistant, or through computerized formats, and conveyed the message that the brain can modify its neural connections through learning, with neuroplasticity mechanisms closely linked to one’s ability to improve knowledge and skills. The duration of these interventions ranged from reading a brief text (a few minutes) to eight sessions of 25 min, with an average of three one-hour sessions. These studies spanned from age six to adulthood and observed effects on motivation, general achievement, reading achievement, mathematics achievement, and some inhibition tasks, like the letter version of the Eriksen Flanker task, and the Go/no-go task (see the original article for more details). This meta-analysis highlights moderating variables that could explain these inconsistencies, showing that the effect of teaching neuroplasticity would be all the stronger with “at-risk” students in mathematics ($g = 0.78$), possibly due to a more fixed mindset at the outset in these students [24,25] and in this domain [26]. According to this meta-analysis, “at-risk” students are those who have vulnerability factors that may hinder their achievement, such as low prior achievement. To our knowledge, however, no research has studied the impact of teaching the concept of neuroplasticity to students who, without necessarily being “at risk” or failing at school, frequently make errors in tasks that require inhibitory control. Yet, teaching the concept of neuroplasticity is specifically aimed at these students, since it promotes inhibitory control in students for whom it appears more difficult to mobilize. Moreover, inhibitory difficulties are frequently associated with academic difficulties, particularly in mathematics [27], which, in turn, are associated

with a more fixed mindset [24,25,28,29]. Thus, teaching students the concept of neuroplasticity seems to represent an interesting avenue, particularly for students who frequently make errors in tasks requiring inhibitory control. This could indeed facilitate the mobilization of inhibitory control and ultimately positively influence their performance, via certain motivational variables.

Most of the research examining the relation between a better understanding of neuroplasticity, subsequent mobilization of brain mechanisms and school performance has explained this relationship using mindset theory, which would act as an intermediate variable. According to mindset framework, a student’s conception of his or her skills - i.e., whether he or she perceives them as modulable - would influence his or her reaction to mistakes. Indeed, when a student with a fixed mindset receives negative feedback, since he believes that he cannot improve, he would tend to perceive this mistake as confirmation of his inability to succeed the task, and therefore to disengage. A growth mindset, on the other hand, would have a positive effect on the student’s reaction to negative feedback; since he believes he can improve, this student would perceive his mistake more as an opportunity to improve his skills, and therefore as a challenge [17,30]. Yet, although this theory seems to provide a coherent explanation of the relation between mindset, brain mechanisms and school achievement, it still does not reach consensus within the scientific community, with inconsistent results regularly emerging [23,31–33].

For example, a meta-analysis looked at the broader effects of a growth mindset intervention (with or without explaining the concept of neuroplasticity) on academic performance [34]. The authors conclude that an intervention to foster a growth mindset has a small, but more effective effect on certain subgroups of students, such as those at risk or with low socioeconomic status. However, an important point is highlighted by this meta-analysis. Of all the studies included, 35 % did not carry out a manipulation check, i.e. they did not verify whether the students’ mindset had actually evolved toward a more growth mindset after the intervention. Interestingly, the effect of the intervention on academic achievement in these studies was significant ($p = .005$, $d = 0.18$), whereas it was not in the studies that did a manipulation check ($p = .249$, $d = 0.04$). More intriguingly, among the studies that did perform a manipulation check, almost half (46 %) observed no change in students’ mindset after the intervention, whereas the effect of their intervention on academic performance was significant ($p = .044$, $d = 0.05$). Moreover, studies that did observe a change in students’ mindset were unable to detect a significant effect of the intervention on academic performance ($p = .771$). Two central conclusions can therefore be extracted from these results: on the one hand, interventions used to promote a growth mindset do not appear to have had an impact on mindset, and on the other hand, they do, however, appear to have had significant effects on academic performance. This would mean that the positive effects of this type of intervention on academic performance are perhaps not explained by students’ mindset as such, but rather by another variable, which calls into question the role of mindset as a mediating variable.

In this sense, some researchers argue that perceived competence (or self-efficacy; [35]) may be a more accurate predictor of performance than mindset theory [36–38]. Perceived competence refers to an individual’s evaluation of his or her ability to succeed in a task or activity [39]. This idea of “believing I am capable of succeeding in the task” is sometimes found in mindset theory. However, believing that one can succeed in a task today is different from believing that one will eventually improve in this task and succeed in it in the future. Questionnaires designed to assess mindset, therefore, seem to integrate several possibly distinct ideas (intelligence, knowledge, skills, perceived control, role of effort, error perception, etc.), which is likely to explain, at least in part, the divergent results observed in the studies. As this integration of different motivational concepts, without necessarily distinguishing them, risks generating unwanted variability in the data, it appears necessary to dissociate them. We therefore proposed a new motivational

model, inspired in part by the Expectancy-Value theory [40,41], but integrating concepts from mindset theory and distinguishing them from one another. We have identified four motivational constructs which, although interrelated, are semantically distinct. The first refers to the central idea of mindset theory, the belief that skills develop and are malleable, that we've named *Perceived Skills' Malleability*. This idea is distinct from students' *Perceived Control* over their success, i.e., whether they believe they have control or power over the causes of their success. Another concept concerns *Error Perception*, which is the belief that error can either be a tool for learning or, on the contrary, a confirmation of inability or lack of skills. Finally, as mentioned above, *Perceived Competence* refers to the student's belief in his ability to succeed at the task. This distinction between constructs could possibly allow for a more accurate prediction of a student's motivation to engage or not in a task. Mindset theory has been developed to explain why some students become discouraged and give up when faced with errors, while others perceive them as challenges to be overcome and engage in the task willingly. Then, the question is: what leads a student to decide to engage in a task and to put in the effort (or other goal-directed behaviors) required to accomplish the task? Research in this field provides some insights into this question, and motivational beliefs, such as the four constructs presented above, seem to be part of the answer. Research indicates that, in general and for any behavior, the brain performs a cost-benefit analysis to determine whether a behavior is worth engaging in [42–44]. In other words, it assesses whether the potential benefits, such as passing an exam or simply getting better, are worth the costs involved in achieving them, such as the cognitive effort required to study. For instance, the Expected Value of Control (EVC) theory proposes that individuals make control allocation decisions by weighing expected benefits against anticipated control costs [43]. It highlights how both rewards and errors can drive adaptive adjustments—rewards may enhance performance, while errors can lead to post-error slowing [43]. Of course, this analysis also considers the student's perceived likelihood of success (or of achieving the benefits), in relation to the costs they anticipate will be necessary to succeed. The balance of this analysis would thus determine whether the individual will engage or not in the behavior, and to what extent. The value of costs and benefits is influenced by various factors, such as the time of day or the level of fatigue, as well as the usefulness and importance attached to the activity, and the interest and pleasure felt in performing it [41,45]. The result of this analysis will determine the student's level of commitment; if they believe that their effort will not only be sufficient to succeed in the task, but that the benefits also outweigh the costs, they'll put in more effort, be more attentive, mobilize more inhibitory control, use a variety of strategies and demonstrate perseverance in the face of difficulties – all goal-directed behaviors that increase the likelihood of success [46]. Conversely, if they either estimate a low probability of success or that the costs do not outweigh the benefits, they will probably choose not to commit, as this would constitute an unnecessary energy expenditure. By integrating these theoretical perspectives, one can assume that to encourage students' commitment, the perceived costs should be minimized while maximizing the potential benefits, but it is also essential that they feel they can succeed. If students believe that they will not succeed at the task despite the costs involved, they are unlikely to invest in it, regardless of their perceptions of their skills' malleability, of control and of error. The perceived competence in a task consequently seems to be a decisive condition for any decision to commit to it. The cost-benefit analysis is therefore influenced by many factors, including the beliefs presented above. We therefore drew upon these various models to develop an integrated framework that incorporates their key elements while distinguishing itself through a clear distinction of the four motivational variables previously discussed, and by placing particular emphasis on the unique role of perceived competence. The model emerging from these considerations is shown in Fig. 1.

Considering the above, the present research was carried out with students who frequently make errors in mathematical tasks requiring

inhibitory control, since students tend to have more of a fixed mindset in this domain. The effects of teaching neuroplasticity were thus examined in the specific context of a counterintuitive mathematics task, namely comparing fractions. It aimed to answer the following question: "What are the effects of teaching the concept of neuroplasticity on motivation, mobilization of inhibitory control and performance on a counterintuitive task?"

Rather than simply determining whether the intervention has positive effects on performance, this research aimed to better understand why and how this intervention might have such impacts, by also studying certain motivational variables as well as the inhibitory control-related brain mechanisms involved in this phenomenon, using neuroimaging. Neuroimaging studies have shown that regions associated with inhibitory control include primarily the anterior cingulate cortex (ACC), the dorsolateral prefrontal cortex (DLPFC), and the ventrolateral prefrontal cortex (VLPFC). The anterior cingulate cortex is more associated with the detection of conflict or interference in information processing [47], while the dorsolateral prefrontal cortex helps maintain different pieces of information in working memory and compares them to determine what needs to be inhibited [48]. Finally, the ventrolateral prefrontal cortex is primarily responsible for the mobilization of inhibitory control itself [49].

Thus, to answer the research question, differences between an experimental group, receiving explanations about neuroplasticity, and a control group, receiving a control intervention, were studied. Inhibitory control was inferred from both fMRI data (mainly via the activation of ventrolateral prefrontal cortex [VLPFC]) and response times [50]. In light of the results obtained from previous research, the research hypotheses were translated as follows:

1. An increase in motivation in the experimental group (measured by a motivational questionnaire) will be observed following the intervention, in contrast to the control group;
2. Compared with the control group, teaching the concept of neuroplasticity to the experimental group will lead to greater mobilization of inhibitory control during counterintuitive trials of the fraction comparison task, reflected both by greater activation of brain regions associated with inhibitory control (mainly the ventrolateral prefrontal cortex) and by longer response times;
3. This mobilization of inhibitory control will be associated with higher accuracy in the fraction comparison task in the experimental group, compared with the control group;

2. Method

2.1. Participants

This comparative experimental study was carried out with students aged 10 to 12. This age group was selected based on literature indicating a discernible difference in students' reaction to mistakes depending on their mindset [51]. Dweck [51] indeed suggests that while younger students may exhibit a fixed mindset, it is typically around ages 10 to 12 that a more entrenched fixed mindset can detrimentally affect their reaction to failure, potentially undermining their motivation and impacting their academic performance. Early intervention with students therefore seems desirable, but studying this phenomenon in younger students may prove more arduous, either due to their limited understanding of these concepts [52], or the greater methodological investment required to assess motivational constructs in this age group. Furthermore, the choice of the fraction comparison task also contributed to the choice of age group, since in Quebec and in many countries, it is at this school level (5th–6th grade in Quebec) that fraction comparison is covered. Participants were recruited from French-speaking elementary schools in the Montreal area (Québec, Canada), mainly via an online ad posted on social media.

The initial selection criteria for participants were: (1) aged between

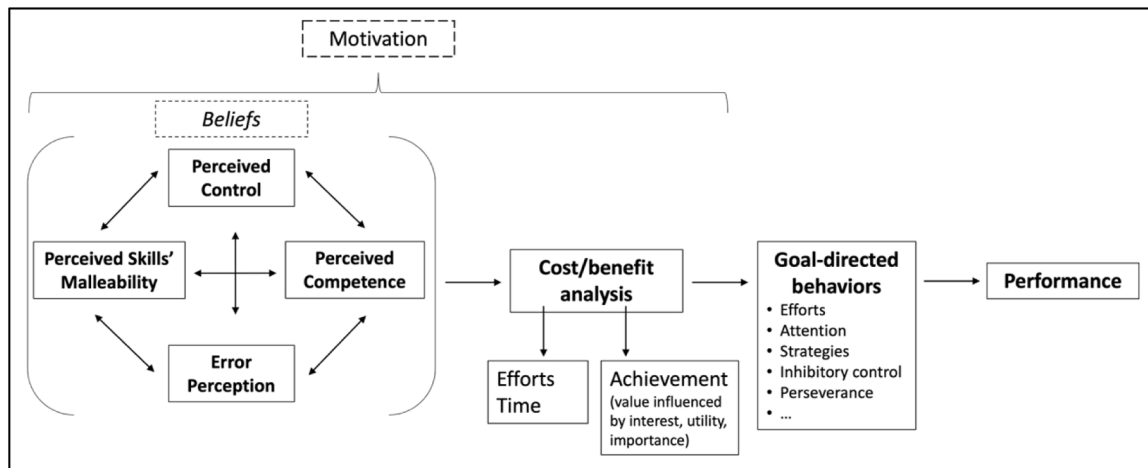


Fig. 1. Model illustrating the presumed relationships between different motivational constructs and their influence on student behavior.

10 and 12 years old; (2) right-handedness; (3) demonstration of specific errors as indicated by the administered mathematical questionnaire (see Questionnaires section); and (4) scoring below average on the motivational questionnaire (see Questionnaires section). The initial sample consisted of 58 participants who were randomly assigned to either the experimental or the control group. 10 participants were then excluded on the basis of the mathematical pre-selection questionnaire (selection criterion 3, see Questionnaires section), three others because their results on the fraction comparison task were considered extreme (± 3 SD), and another because of unusable brain data (incomplete brain imaging). The final sample thus consisted of 44 participants with 22 participants in each group (mean age was 11.4 years old; $SD = 0.73$). Participants first completed the online mathematical pre-selection questionnaire and the motivational questionnaire. Analyses confirmed that both groups were equivalent in terms of sex, age, school year, and mathematical skills). Selected participants received one or other of the interventions (see Interventions section) at the *Unité de neuroimagerie fonctionnelle* (UNF) of the *Centre de recherche de l'Institut universitaire de gériatrie de Montréal* (CRIUGM), and then performed the fraction comparison task inside the research center's fMRI scanner. The children and their guardians gave free and informed consent by signing a consent form. The study was approved by the *Comité d'éthique de la recherche vieillissement-neuroimagerie* (no CER VN 19-20-25) of the CRIUGM.

2.2. Questionnaires, interventions and task

2.2.1. Pre-selection questionnaire in mathematics

To select participants who met the mathematical pre-selection criteria, children interested in the study completed a short online questionnaire designed to identify the profile of errors sought in counterintuitive mathematical situations. The questions focused on four counterintuitive concepts (fractions, decimal numbers, perimeter/area and probability) requiring inhibitory control. The error profile sought consisted in generally succeeding intuitive items and frequently committing errors in counterintuitive items. Since the intervention aimed at promoting the general mobilization of inhibitory control (rather than being directly linked to the concept of fraction), we sought to select participants who made inhibitory-related errors beyond just those occurring during fraction comparison. In other words, we aimed to include individuals who experienced an 'interference effect' between intuitive and counterintuitive items in mathematics, not limited solely to fraction comparison, to avoid selecting participants based on difficulties specifically related to fractions rather than inhibitory control. Operationally, participants needed to successfully complete more than half of the intuitive fraction comparison items to demonstrate comprehension of this concept. Additionally, they had to perform better on intuitive

items compared to counterintuitive ones across the entire questionnaire, indicating susceptibility to interference in the counterintuitive condition. As mentioned previously, 10 participants were excluded based on this criterion.

2.2.2. Motivational questionnaire

A new motivational questionnaire was developed from the model presented in Fig. 1, and validated ($\omega = 0.908$; a four-component principal component analysis supported the theorized structure), in order to measure more precisely four motivational variables (perceived skills' malleability, perceived control, error perception and perceived competence) that are likely to play a role in the relationship between a neuroplasticity/growth mindset intervention and performance. The questionnaire was largely inspired by previous questionnaires about mindset, perceived competence or motivation more generally [25,36,53,54]. See Appendix A for an English translation of the full questionnaire. Participants completed the motivational questionnaire in pretest and posttest and were asked to rate their level of agreement with each statement using a six-point Likert scale (from Strongly disagree to Strongly agree). Initially, it was intended that only students with below-average scores on each of the four constructs would be selected. However, it was difficult to recruit participants who matched this criterion perfectly, especially as the questionnaire results for this sample showed a ceiling effect. No participant was therefore excluded based on the motivational questionnaire.

2.2.3. Interventions

The experimental group watched, in the testing room, a 4-minute 33-second video in French on the concept of neuroplasticity in a popularized way to suit the age of the students (link to video [French and English versions available]: <http://www.labneuroeducation.org/cerveau>). The content of this video has been thought through to correspond to the four motivational variables measured by the motivational questionnaire and is inspired by previous research and varied teaching material (e.g., [22]). It first introduces the notion of *neuroplasticity* by explaining the idea that neuronal connections change and strengthen to become more effective. It then elaborates that when neuronal connections strengthen during learning, it leads to improved skills and competencies. The idea of *control* is then tackled by detailing how neuroplasticity can be influenced. For instance, it is explained that effort and the use of various strategies, such as practice, lead to the strengthening of neuronal connections. The next segment deals with the notion of *error*, describing it as necessary for learning. It is mentioned, for example, that it is by paying attention to feedback that we can avoid making the same mistakes again. Emphasis is also placed on the idea that if a task is difficult, it indicates learning is occurring, and therefore, perseverance is necessary to

strengthen the neuronal connections associated with this specific learning. Finally, the video concludes with a discussion of *perceived competence*, explaining that when students believe they can perform a task, their brain becomes more activated compared to when they believe they cannot succeed. A brief summary reiterates the key elements presented (see [55] for a popular science article for teachers on this video, in French).

After viewing the video, participants in both groups were asked to summarize what they had understood. The experimenter did not intervene at this stage, except to encourage the participant to elaborate further if necessary. This not only aimed to ensure comprehension among those in the experimental group but also aligns with research suggesting that elaborating on explanations can enhance retention of newly acquired knowledge [56,57]. The video was then viewed again (the participant had been warned of this before the first viewing), to provide an opportunity for repetition and thus also reinforce the neural networks linked to this new learning [58]. Three "true or false" comprehension questions were finally asked to ensure that the participant had understood the main messages ("When you learn, your brain changes."; "When the connections in your brain strengthen, it makes you improve."; "You can't do anything to help your brain change.").

To isolate the effects of teaching the concept of neuroplasticity, the control group received an intervention similar in format to that of the experimental group, but with different content. As the production of animated videos can be costly, an existing video was chosen as the **control intervention**. This video, produced by the French Environment and Energy Management Agency (ADEME), addresses climate change. It was chosen as a control intervention for its duration, animation style, and level of popularization, which matched the desired characteristics of the neuroplasticity video.

2.2.4. Task

A fraction comparison task was selected to measure participants' mathematical performance and mobilization of inhibitory control. The task consisted in determining which of two fractions is the largest. This

task is one of the best-documented examples involving counterintuitive situations requiring the mobilization of inhibitory control [6,9,11,59]. Participants therefore had to determine which of two fractions represented the higher quantity by pressing the button (on an answer box) located on the side of the larger fraction (right button for right fraction and vice versa). As mindset theory is primarily based on participants' reaction to mistakes, feedback was given between each trial, indicating whether the answer was correct or incorrect using a green check mark or a red "x". The feedback also illustrated fractions using circles divided into equal parts according to the denominator of the fraction they represented, with the numerator corresponding to the number of shaded parts (see Fig. 2). The instructions provided an example of a pair of fractions and reminded participants that they had to compare the values of each fraction in the pair. They were instructed to respond within five seconds, answering as quickly as possible while minimizing errors. During performance, each pair of fractions was presented until the participant pressed a button, or for a maximum of five seconds, before feedback was presented for 3.5 s. Between each item (stimulus and feedback), a fixation cross appeared for a random duration varying between 2 and 3 s [60]. Total task duration was approximately 20 min. Participants first practiced the task in the testing room before the imaging session, completing five practice items to ensure comprehension.

This fraction comparison task was in part inspired by Gómez et al. [6, 7], but has been adapted for the present study. Indeed, the use of fMRI poses several constraints, for instance in terms of the number of stimuli presented to participants in the device. As the tasks in previous studies did not take place during an fMRI session, they included an insufficient number of items. For the purposes of the present research, some items were taken from the tasks of previous studies and others were added. The designed task thus comprised 48 different pairs of fractions that were presented twice (fractions were reversed in the second presentation), for a total of 96 items. The 96 items were divided into three sets of 32 items, which were presented randomly to each participant. The 48 fraction pairs were divided into four conditions, as in most fraction comparison tasks in previous studies. Firstly, half of the items (24) were

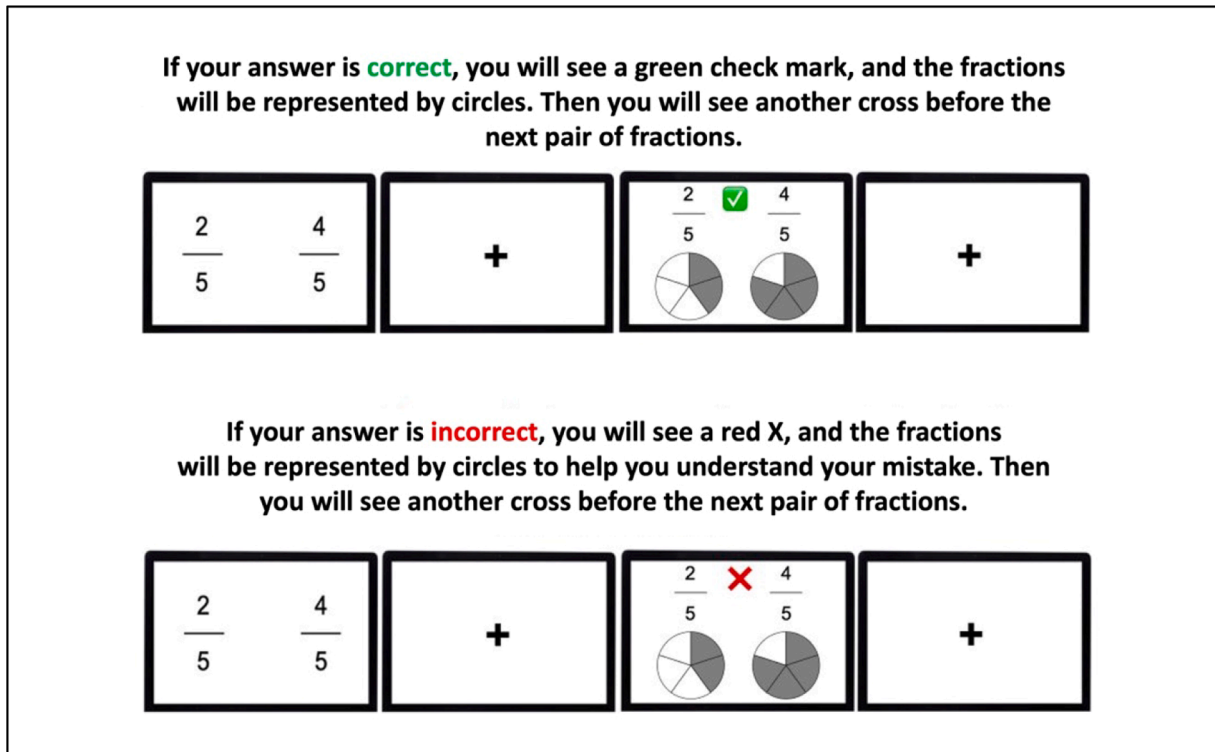


Fig. 2. Excerpt from the task instructions concerning feedback (free translation).

intuitive and the other half counterintuitive. Then, to prevent participants from "automating" a response strategy when pairs of fractions have either an identical numerator or denominator (e.g., "when the denominator is the same, I can trust my intuition, and when the numerator is the same, I have to answer the opposite of my intuition"), pairs of fractions without common components, i.e. where none of the four components are identical, were included. The four conditions were thus: (1) intuitive items with a common component, (2) counterintuitive items with a common component, (3) intuitive items without a common component and (4) counterintuitive items without a common component. The 48 pairs of fractions also met certain equivalence criteria: they were proper fractions, irreducible, none of them had 10 as the denominator, and the denominator was always less than 20. The distance between the two fractions of a pair was also controlled, and no significant difference was observed between the four task conditions ($F = 0.182, p = .908$). See [Appendix B](#) for all original task stimuli.

However, despite the many precautions taken to control as many variables as possible in the design of this task, a particular pattern of responses was observed in Conditions 3 and 4, i.e., conditions without common components. Indeed, the counterintuitive items were performed much better than the intuitive ones for these conditions. After closer examination, it has been noticed that several counterintuitive items represented a fraction for which "only one piece is missing to make a whole" (e.g. 4/5), unlike the intuitive items. This suggests that instead of relying on expected automatism (choosing the larger number), participants compared each fraction to a whole, thereby simplifying the task in the counterintuitive condition. Indeed, some authors point out that students may employ strategies other than the expected automatism (the natural number bias) or the appropriate algorithm, such as the gap thinking strategy [9]. This strategy involves comparing the absolute difference between the numerator and denominator of each fraction and concluding that the largest fraction is the one with the smallest difference. As the gap thinking strategy does not have the same effect on items "with" and "without" common components, and as the inclusion of items "without common components" leads to greater variability in the strategies used, some researchers decide to consider these items as buffers (e.g., [9]). Since the conditions without a common component were not the focus of this study and participants did not seem to rely on the expected automatism to respond, data from these conditions were excluded from analysis. Only data from Conditions 1 and 2 (with a common component) were analyzed.

2.3. MRI acquisition and analysis

Imaging was performed on a 3.0 T Prisma Fit (Siemens Medical Systems, Erlangen, Germany) using a 32-channel head coil. To minimize head movement, the head of the participant was stabilized with foam cushions. Functional images were obtained using a single-shot gradient echo EPI sequence sensitive to blood oxygen level-dependent (BOLD) contrast (TR = 923 ms, TE = 30 ms, FA = 59°, FOV = 220 mm, matrix size = 74 × 74, voxel size = 3 × 3 × 3 mm, interleaved). Forty-two 3 mm thick transverse slices with a distance factor of 0 % were acquired parallel to the AC-PC line. Structural images were obtained using a T1-weighted 3D MPRAGE sequence (TR = 2400 ms, TI = 1000 ms, TE = 2.17 ms, FA = 8°, FOV = 224 mm, matrix size = 224 × 224, 1 slab, 176 frames per slab, voxel size = 1 × 1 × 1 mm). Stimuli were presented using E-Prime 3.0 software (Psychology Software Tools, Inc.) on a projection screen in the scanner room, visible to the participant through a mirror mounted above the head coil. Subject responses were collected using a fiber-optic button response system (Psychology Software Tools, Inc., Sharpsburg, Pennsylvania, USA).

Behavioral data (response time and accuracy) were analyzed using the Statistical Package for the Social Sciences (SPSS28). As the motivational data showed a ceiling effect and did not respect normality, a Mann-Whitney U test was first performed to check whether there was a significant difference between the pretest and posttest groups. We then

examined whether significant differences existed between pretest and posttest measurements within each group using the Wilcoxon test. The response times measured for each item of the fraction comparison task were subjected to a two-way repeated measures ANOVA, namely the Group factor (neuroplasticity vs. control intervention) and the Condition factor (intuitive vs. counterintuitive). Accuracies were also analyzed using a two-way repeated measures ANOVA (Group × Condition).

Brain analyses were performed using Statistical Parametric Mapping (SPM8) software (Functional Imaging Laboratory, 2017) running under MATLAB. The functional data of each participant was motion-corrected, co-registered with structural data, and then spatially normalized into the standard MNI space (Montreal Neurological Institute). Head motion was corrected with SPM8 across and within sessions of every subject. The fMRI series were motion-corrected using the standard SPM "spm_realign" procedure, enabling them to be aligned with the mean images calculated by SPM. Normalization was performed using the standard SPM "spm_coreg" procedure that co-registers the individuals' anatomic images to their EPI and allows for a better normalization to the MNI template. The normalized images were then smoothed with an 8 mm Gaussian filter FWHM. Following visual analysis of image quality, no participants were excluded for excessive movement, but one participant was removed due to poor image processing.

The statistical analysis was conducted using the general linear model. Model time courses for each experimental condition were generated based on the hemodynamic response function implemented in SPM8. A random effects flexible factorial design analysis was used to model the interactions between participants and experimental conditions (intuitive vs. counterintuitive) factors as well as modeling global effects for each participant [61]. The two-way repeated measures ANOVA revealed the effect of the interaction (group × condition), highlighting differences in activation patterns between subjects and experimental conditions. The interaction effect and *t*-tests specifying the direction of the interaction effect are reported at the family-wise error (FWE) corrected threshold of $p_{FWE} < .05$ at cluster level (using $p < .005$ at peak level). Furthermore, since our study focuses on research hypotheses concerning a particular brain region (ventrolateral prefrontal cortex [VLPFC]), we also performed a region-of-interest analysis. The WFU PickAtlas tool [62] was used to define the VLPFC region of interest.

3. Results

3.1. Behavioral results

3.1.1. Motivational questionnaire

Regarding the motivational questionnaire, the Mann-Whitney U test for independent samples was first performed to verify whether there was a difference between the groups in pretest, then in posttest, for each of the motivational variables: perceived skills' malleability, perceived control, error perception, perceived competence, and the total motivational score. There were no significant differences between the groups for either the pretest or posttest. Then, to test whether there was a difference between pretest and posttest within each group, the Wilcoxon rank-sum test was performed. [Table 1](#) and [Fig. 3](#) show that there was a difference between pretest and posttest in the experimental group for all motivational variables, except for perceived skills' malleability. In the control group, no significant difference was observed between pretest and posttest.

For perceived skills' malleability, the effect size obtained was $d = 0.13$, which is a small effect size [63,64]. Perceived control and error perception showed medium effect sizes, $d = 0.47$ and $d = 0.43$, respectively, and perceived competence $d = 0.35$, an effect size between "small" and "medium". The effect size for all variables combined (total motivational score) was also medium, i.e. $d = 0.48$.

3.1.2. Fraction comparison task

The results of the two-way repeated-measures ANOVA on task

Table 1

Intra-group differences between pretest and posttest for the motivational questionnaire.

Motivational variables	Experimental group n = 22		Control group n = 22	
	Z	p	Z	p
Perceived skills' malleability	-1.33	0.184	-0.60	0.548
Perceived control	-2.31	0.021*	-0.90	0.369
Error perception	-2.24	0.025*	-0.18	0.856
Perceived competence	-2.96	0.003**	0.00	1.000
Total motivational score	-3.13	0.002**	-0.57	0.566

Note : *p < .05, ** p < .01.

response times reveal no significant interaction effect between group and condition ($F(1, 42) = 0.672, p = .417, \eta^2 = 0.016, d = 0.20$), nor any group effect ($p = .468$). The effect of condition was, however, significant ($F(1, 42) = 15.864, p < .001, \eta^2 = 0.274, d = 0.48$), with response times for the counterintuitive condition being longer than for the intuitive condition, supporting the need for inhibitory control in the counterintuitive condition. Regarding accuracy, the results of the two-way repeated measures ANOVA revealed no significant interaction effect either ($F(1, 42) = 0.574, p = .453, \eta^2 = 0.013, d = 0.27$), nor any group effect ($p = .879$). However, the effect of condition was also significant ($F(1, 42) = 12.34, p = .001, \eta^2 = 0.227, d = 0.64$), with accuracy for the counterintuitive condition being lower than for the intuitive condition. Tables and figures for these analyses are presented in Supplementary Material.

3.2. fMRI data

3.2.1. ANOVA results

The interaction effect of the ANOVA (Group x Condition) was significant for three brain activations, involving the right fusiform gyrus, the left putamen and the left associative visual cortex. Table 2 details these results, which are significant at a family-wise error (FWE) corrected threshold of $p < .05$ at cluster level and based on activations comprising a minimum of 20 voxels.

3.2.2. t-Test results

To verify the direction of the effects observed with the ANOVA, paired t-tests were performed. Results are also presented at a corrected FWE threshold of $p < .05$ at cluster level. However, to identify the direction of interaction for two of the significant regions above (right fusiform gyrus and left associative visual cortex), an uncorrected threshold of $p < .005$ had to be established. The uncorrected thresholds are therefore identified in Table 3 by "unc.", and the three regions identified in the interaction are highlighted in green. Other contrasts, not visible in the interaction effect, showed significant activations. Contrasts not shown in the table showed no significant activation.

In addition to the activations identified in the interaction, three other contrasts were significant at a corrected threshold, namely an activation spanning the ventrolateral prefrontal cortex and slightly the dorsolateral prefrontal cortex, and another associated with the right caudate nucleus, both for the counterintuitive > intuitive contrast in the experimental group. A final one was significant in the right visual associative cortex for the intuitive > counterintuitive contrast in the control group. To verify whether these significant activations were also found in the

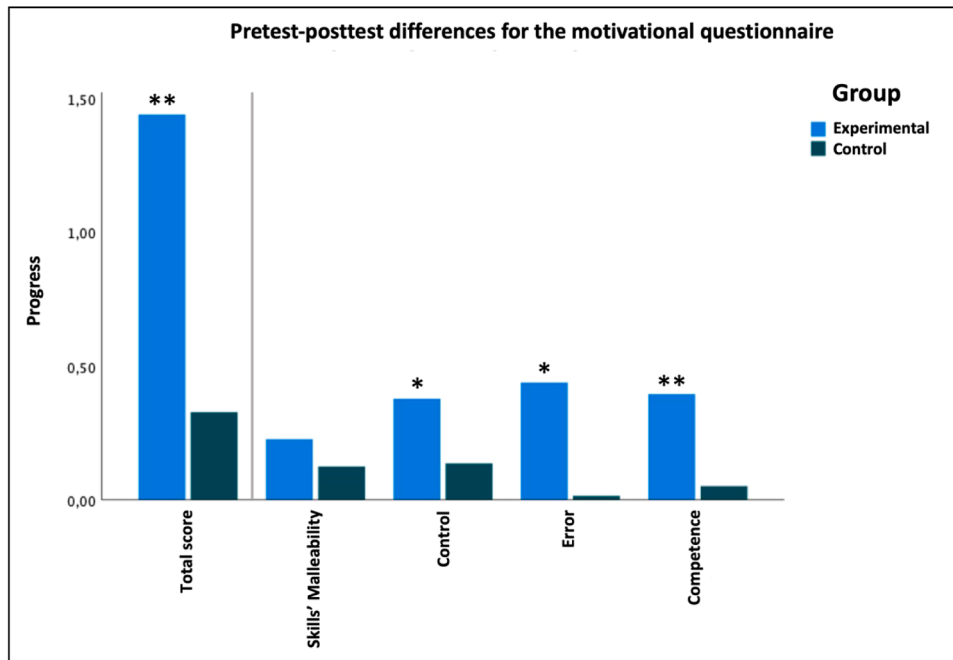


Fig. 3. Differences between pretest and posttest for the motivational questionnaire.

Table 2

Brain regions significantly associated with group (experimental/control) and condition (intuitive/counterintuitive) interaction (ANOVA).

Brain region	Brodmann area (BA)	Coordinates			F	k	p
		x	y	z			
Right fusiform gyrus	BA 37	21	-39	-21	39.79	1958	< .001
Left putamen	N/A	-27	-3	18	26.54	413	< .001
Left associative visual cortex	BA 19	-36	-66	15	17.93	66	.038

Note: Random-effects analysis, $p_{(FWE-cluster)} < 0.05$, min. 20 voxels. Regions are identified using the Talairach atlas (Talairach and Tournoux, 1988).

Table 3

Brain regions significantly more activated for each group (experimental/control) and condition (intuitive/counterintuitive) (paired *t*-tests).

Brain region	Brodmann area (BA)	Coordinates			<i>t</i>	<i>k</i>	<i>p</i>
		<i>x</i>	<i>y</i>	<i>z</i>			
Experimental group							
<i>Counterintuitive > Intuitive</i>							
Right fusiform gyrus	BA 37	36	-36	-18	4.33	17	< .001 (<i>unc.</i>)
Left ventrolateral prefrontal cortex/ Left dorsolateral prefrontal cortex	BA 46/44	-45	27	18	5.15	363	= .001
Right caudate nucleus	N/A	-3	0	24	5.62	214	.020
Control group							
<i>Intuitive > Counterintuitive</i>							
Left putamen	N/A	-27	-12	12	5.36	580	< .001
Right associative visual cortex	BA 19	33	-69	-3	5.87	2958	< .001
Intuitive stimuli							
<i>Control > Experimental</i>							
Left associative visual cortex	BA 19	-36	-63	21	3.27	16	= .001 (<i>unc.</i>)

Note: Random-effects analysis, $p_{(FWE-cluster)} < 0.05$, except identified thresholds, min. 0 voxel. Regions are identified using the Talairach atlas (Talairach and Tournoux, 1988). Regions identified in the interaction effect are highlighted in green.

Table 4

Brain regions significantly associated with group (experimental/control) and condition (intuitive/counterintuitive) interaction (ANOVA, uncorrected threshold).

Brain region	Brodmann area (BA)	Coordinates			<i>F</i>	<i>k</i>	<i>p</i>
		<i>x</i>	<i>y</i>	<i>z</i>			
Left ventrolateral prefrontal cortex	BA 44/45	-36	18	21	17.92	66	< .001
Right caudate nucleus	N/A	-3	0	24	15.03	2	< .001
Right associative visual cortex	BA 19	24	-66	18	10.94	3	.002

Note: Random-effects analysis, $p_{(unc.)} < 0.005$, min. 0 voxel. Regions are identified using the Talairach atlas (Talairach and Tournoux, 1988).

interaction effect results of the initial ANOVA, we applied an uncorrected threshold of $p < .005$ to it. Table 4 shows these three other activations in the interaction effect, at an uncorrected threshold.

Fig. 4A shows all significant activations at an uncorrected threshold for the interaction effect.

3.2.3. Region-of-interest analysis

As previously mentioned, the ACC, and the DLPFC are also regularly associated with inhibitory control, but the VLPFC is primarily responsible for the mobilization of inhibitory control itself [49]. Therefore, a region-of-interest analysis was carried out, since the initial hypothesis targeted a specific region, namely the ventrolateral prefrontal cortex. As this region is relatively large (it is bilateral and encompasses three subdivisions), we first attempted to target the left VLPFC, as several studies associate it with mathematical tasks, notably fraction comparison [65,66]. We then used three masks, one for each of the subdivisions of the VLPFC: *pars opercularis*, *pars triangularis* and *pars orbitalis*. No prior hypothesis was formulated concerning the anticipated subdivision, as the specificities of each are still more or less well defined in the literature. During the analyses, these subdivisions were also defined using the WFU PickAtlas tool [62]. The results for *pars opercularis* and *pars orbitalis* showed no significant activation at a corrected threshold, while those for *pars triangularis* showed a significant activation in the left *pars triangularis* of the VLPFC ($p = .048$). This is shown in Table 5 and Fig. 4B

Furthermore, in order to observe whether the interaction effect in the left VLPFC reflects differences in relative activation or deactivation, individual mean beta values for this activation cluster were extracted for regressors of intuitive and counterintuitive conditions. As shown in Fig. 5, greater VLPFC activation was observed in the experimental group for the counterintuitive condition, with the ANOVA interaction (Group x Condition) being significant ($F(1, 42) = 10.22, p = .003, \eta^2 = 0.196$), with a mean effect size of $d = 0.56$. Interestingly, the mean beta value for this contrast (counterintuitive > intuitive in the experimental group) was the only one showing a positive value.

3.2.4. Further analysis

Since the intervention had a significant impact on motivation and brain activity in the experimental group, a complementary analysis was carried out to verify whether there was a relationship between the change in motivation and brain activity in the left VLPFC in the counterintuitive condition. A multiple linear regression was therefore performed to test the extent to which the four motivational variables could predict brain activity, i.e. to determine the relative weight of each motivational variable in brain activity. The correlation matrix showed that the only variable significantly correlated with brain activity was the change in perceived competence, with a coefficient of medium size ([63,64]; $r = 0.32, p = .04$). Correlations between the other variables and brain activity were all non-significant. In the multiple linear regression, these three other variables were excluded from the model, as the models including them were not significant. The model retained was the one including only the change in perceived competence ($F(1, 42) = 4.773, p = 0.04$). The R^2 was 0.102, indicating that the change in perceived competence explains around 10.2 % of the variance in brain activity. The regression equation was as follows: $A = -0.328 + 1.27x$ (A representing brain activity and x representing the change in perceived competence). Confidence intervals indicate that it is 95 % certain that the slope predicting brain activity from change in perceived competence is between 0.10 and 2.44.

4. Discussion

4.1. Hypothesis 1: effects of teaching neuroplasticity on motivation

Based on the literature on interventions designed to influence students' mindset, the first hypothesis predicted an increase in motivation in the experimental group following the intervention, compared with the control group. Since research on mindset has observed divergent and controversial results, we hypothesized that these discrepancies might be explained by the integration of several related but distinct variables into mindset theory and questionnaires. Confounding variables can indeed induce "noise" in the data, leading to inconsistent results. We previously

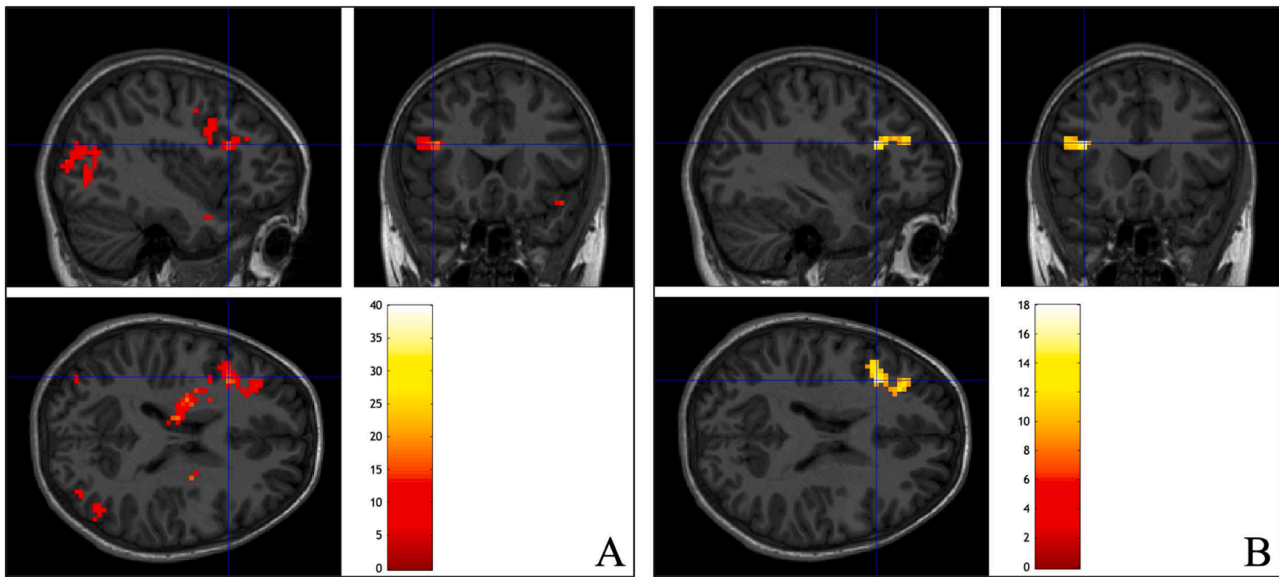


Fig. 4. A. Whole brain volume analysis: significant activations at uncorrected threshold $p_{(unc.)} < 0.005$ for the interaction effect. B. Analysis by region of interest: significant activation of the left ventrolateral prefrontal cortex at a corrected threshold $p_{(FWE-cluster)} < 0.05$, for the interaction effect.

Table 5

Interaction effect of group (experimental/control) and condition (intuitive/counterintuitive) by region-of-interest analysis with left lateralized mask of ventrolateral prefrontal cortex *pars triangularis*.

Brain region	Brodmann area (BA)	Coordinates			F	k	p
		x	y	z			
Left ventrolateral prefrontal cortex	BA 44/45	-36	18	21	17.92	36	.048

Note: Random-effects analysis, $p_{(FWE-cluster)} < 0.05$. The mask is defined with the WFU Pickatlas.

distinguished four motivational variables regularly found in the mindset literature: perceived skills’ malleability, perceived control, error perception and perceived competence. A new motivational questionnaire was developed from these four variables, and then validated for use as a measure of motivation in the present project, both in pretest and posttest.

Results show that teaching neuroplasticity had a significant impact on motivation overall and on all motivational variables, except perceived skills’ malleability. Interesting effect sizes were found, particularly for a 5-minute intervention, for perceived control ($d = 0.47$), error perception ($d = 0.43$) and perceived competence ($d = 0.35$). It seems, however, that teaching students that their brain is plastic is not necessarily enough to increase their perception of their skills’ malleability. This result is even more interesting given that the perception of skills’ malleability refers to the belief that skills can develop, which is at the heart of mindset theory. Indeed, several research studies have observed that an intervention aimed at inducing a growth mindset failed to do so, i.e., the intervention could sometimes influence achievement, but failed to change students’ mindset [34]. These prior findings align with the outcomes of this research: the positive results observed in other studies regarding achievement may stem from factors other than the perception of skills’ malleability. Indeed, our results suggest that instructing students on the plasticity of their brains, as well as emphasizing additional factors like practice, effort, attention to mistakes, and self-belief in one’s own abilities, can significantly impact their perceived control, error perception, and perceived competence. These elements likely play a crucial role in the observed effects. Indeed, some authors point out that most interventions aimed at making students aware that their skills are malleable also include encouragement for effort, practice, perseverance, use of various strategies, error perception, etc. [67]. Therefore, it is plausible that most interventions designed to promote a

growth mindset exert a stronger influence on these variables, which are more peripheral constructs within mindset theory. It should be noted, however, that the participants in the present research already had a relatively high perception of their skills’ malleability, which may also explain why no significant differences were observed between pretest and posttest in the experimental group.

4.2. Hypothesis 2: effects of teaching neuroplasticity on the mobilization of inhibitory control

4.2.1. Brain results

The first part of the hypothesis concerning inhibitory control predicted greater activation of the ventrolateral prefrontal cortex in counterintuitive trials than in intuitive ones in the experimental group compared with the control group.

Whole-brain volume analysis showed a significant interaction effect for an activation cluster in the left VLPFC, at an uncorrected threshold, and the direction of this interaction was found in results from simple contrasts (paired *t*-tests). Consistent with the hypothesis, this difference reflects greater activation of the left VLPFC in the counterintuitive condition, compared to the intuitive condition, for the experimental group, compared to the control group. When analyzed by region of interest, this activation is significant at a corrected threshold with a medium effect size ($d = 0.56$), in the *pars triangularis* subdivision. Although several fMRI studies associate the right VLPFC with inhibitory control (e.g., [68]), several other studies and literature reviews emphasize the importance of the left VLPFC in this mechanism [69–72]. Research by Masson et al. [73] and Allaire-Duquette et al. [74] also showed greater activation of the left VLPFC when evaluating counterintuitive stimuli in science. In addition, several studies observed activation of the left VLPFC during mathematical tasks [75,76], particularly during fraction

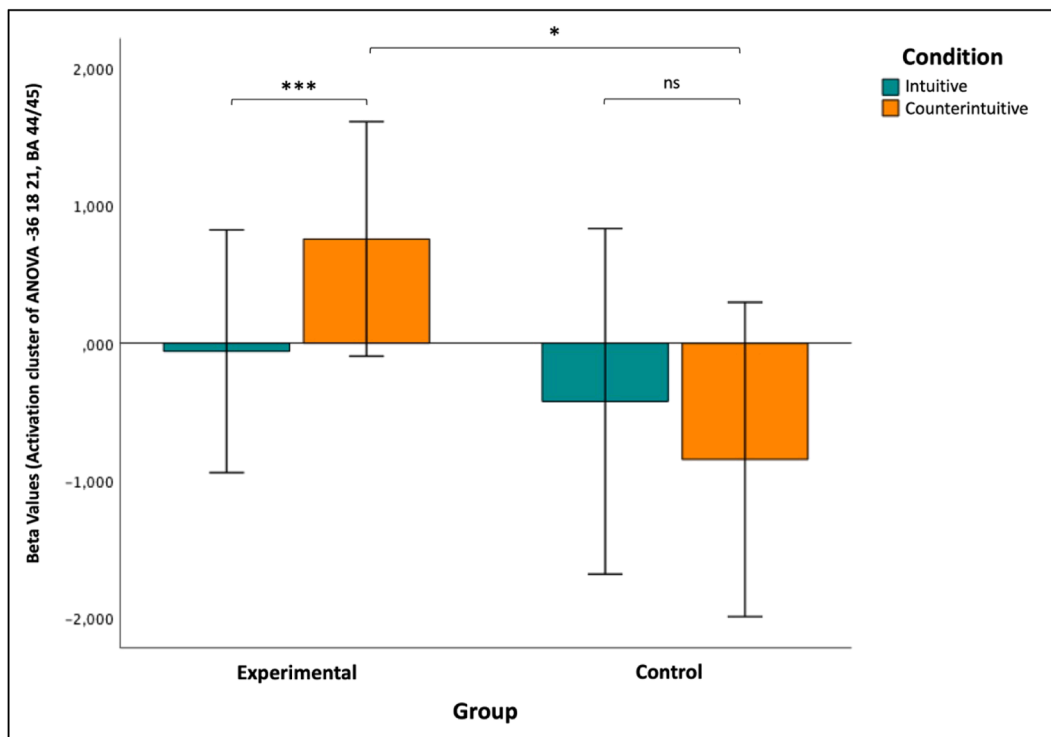


Fig. 5. ANOVA of mean beta values of intuitive and counterintuitive conditions averaged over all voxels from the activation cluster in VLPFC ($-36\ 18\ 21$, BA 44/45). * < 0.05, ** < 0.01, *** \leq .005.

comparison [65,66].

Regarding the subdivisions of the VLPFC, no hypothesis had previously been formulated, since the specificities of each are still more or less clear in the literature. However, it seems that the *pars opercularis* (corresponding approximately to BA44) and the *pars triangularis* (corresponding approximately to BA45) have very similar functions and are part of the same system [77]. These two subdivisions are regularly associated with working memory and response inhibition [68,77]. For example, they are more activated in fraction comparison tasks when the items are more difficult (in counterintuitive conditions [65] or when the numerical distance between the two fractions decreases [66]). More specifically, the *pars triangularis* appears to be associated with a wider network regulating inhibitory control, including the insula, the caudate nucleus and the supplementary motor area [78]. The significant activation obtained in the *pars triangularis* in the experimental group during the counterintuitive condition is therefore consistent with the literature, and probably reflects a greater allocation of attentional resources to counterintuitive stimuli, as well as an initiation of the inhibitory control mechanism to overcome the automatism predominant in this condition. These findings are also consistent with studies using EEG [19–21] concluding that a growth mindset was associated with greater attention to task-relevant elements.

As with the VLPFC, two other regions were significantly more activated in the experimental group in the counterintuitive condition: the right caudate nucleus and the right fusiform gyrus. The caudate nucleus is part of networks involved in cognitive and emotional processing [79]. Although part of the striatum, involved in the brain's reward system, the caudate is also associated with the planning of goal-directed actions, such as response selection [80] and the control of interference, notably during classic inhibitory control tasks [81,82]. Other studies specify that the participation of the caudate nucleus in a broader functional network associated with inhibitory control would be partly related to the anticipation of a stop signal [83,84] and subsequent preparation for the implementation of inhibitory control [85,86]. This suggests that the activation of the caudate nucleus observed in the counterintuitive

condition in the experimental group of this research could reflect an anticipation of the need to inhibit an automatism in this condition and a preparation to do so.

The fusiform gyrus, on the other hand, is an extension of the visual areas and thus performs complex visual functions, such as face or object recognition [77]. It is also activated when imagining writing or drawing and is therefore also involved in imagining visual elements [87]. In the present study, this suggests that participants in the experimental group possibly tended to pay more attention to the visual elements of the stimuli in the counterintuitive condition, and perhaps even to the imagined representation of fractions as circles divided into parts. Since relying on the automatism in the counterintuitive condition led to errors, it is possible that participants attempted to visualize fractions as portions of circles, similar to the feedback provided throughout the task.

The other significant activations observed were in the intuitive condition in the control group, namely the left putamen and the left and right associative visual cortices. The putamen is generally associated with lower-level cognitive functions, i.e. a task that requires less attention or cognitive energy and is more habitual or automatic [80,88]. The literature furthermore associates it with the brain's reward and reinforcement system [88,89]. Putamen activity may also reflect the level of confidence regarding a decision made [88], probably because being confident in one's prediction leads to the anticipation of a reward. In the present research, the activation of the putamen in the intuitive condition in the control group therefore suggests that participants were able to answer rather easily (which accuracies confirm) and relatively automatically, feeling confident in their answer and anticipating positive feedback. Finally, the greater activation of the left and right associative visual cortices in the control group during the intuitive condition suggests that the participants in this group processed the information more sensorially.

To sum up, it seems that participants of the two groups activate partially different brain regions when comparing fractions. In fact, the results suggest that the students who watched the neuroplasticity video activated regions associated with inhibitory control (ventrolateral

prefrontal cortex and caudate nucleus) more than those in the control group for the counterintuitive condition, whereas those in the control group seemed to process information more sensorially in the intuitive condition. The latter also appear to be more focused on the sense of reward they derive from anticipating success on intuitive ("easy") items, whereas students in the experimental group seem to devote more attentional resources to counterintuitive items and prepare to implement inhibitory control to avoid falling into the automatism "trap".

4.2.2. Response times

However, the second part of Hypothesis 2 concerning inhibitory control predicted longer response times in the experimental group for the counterintuitive items, which generally results from the mobilization of inhibitory control [50], which was not observed. An explanation emerges when we also consider accuracy results. Indeed, both groups have similar accuracy, so the experimental group does not perform any better. The observed response times could therefore mean that, although participants in the experimental group mobilized brain regions related to inhibitory control more than those in the control group in the counterintuitive condition, this does not appear to have been sufficient to lead them to the full implementation of inhibitory control, which would have been reflected by longer response times and higher accuracy in this condition, compared to participants in the control group.

4.3. Hypothesis 3: effects of teaching neuroplasticity on performance in the fraction comparison task

Finally, the performance hypothesis predicted higher accuracy on the fraction comparison task in the experimental group, compared with the control group, as a result of a presumed greater mobilization of inhibitory control in this group. However, since both groups show high accuracy, it seems that they have both quite successfully inhibited the automatism in most situations, and as mentioned, that even though participants in the experimental group show more brain activation related to inhibitory control than participants in the control group, they probably failed to complete the inhibition of the automatism in the missed trials. It is therefore quite logical to observe no difference between the groups in terms of accuracy. Indeed, as with response times, we observed a condition effect, i.e. significantly lower accuracy for counterintuitive items than for intuitive items in each group, supporting the idea of the need for inhibitory control in this first condition. However, there were no significant differences between the groups, supporting the latest proposed interpretation of inhibitory control, i.e. that participants in the experimental group probably failed to mobilize inhibitory control sufficiently to lead to its full implementation in the missed trials. However, since accuracy is very high in both groups, it's also possible that there wasn't enough room for the experimental group to demonstrate higher accuracy than the control group.

These results also provide a potential new explanation for the often-contradictory findings on the effect of mindset interventions on achievement. Indeed, they show that it is possible for this type of intervention to have positive effects on brain activity, but for these effects to be insufficient to impact on performance-related behavioral outcomes. As most studies don't have neuroimaging measures, there is a risk of overlooking brain-level effects that modulate behavioral effects. Studies may therefore sometimes conclude that the intervention had no effect, even though it may have had brain-level effects, which is a step in the right direction [90].

4.4. Relationship between motivation and mobilization of inhibitory control

Although not a hypothesis as such, this research also sought to verify whether motivation acts as a moderating variable in the relationship between a neuroplasticity intervention and the mobilization of inhibitory control. In other words, since much research attributes the effects of

teaching neuroplasticity on goal-directed behaviors (e.g., mobilization of inhibitory control, attention, effort, etc.) to a change in mindset (motivational beliefs), the present research sought to verify the existence of this relationship between change in motivation and mobilization of inhibitory control. Linear regression was thus performed to test which of the four motivational variables predicted inhibitory control-related brain activity. Only the change in perceived competence following the intervention was significantly linked to the ventrolateral prefrontal cortex activation, with the other variables showing no significant association with brain activity. Indeed, the overall correlation coefficient for the regression obtained ($r = 0.319$) is medium-sized and significant ($p = .035$), explaining 10.2% of the variance. This means that the change in perceived competence partially, but significantly, predicts brain activity related to inhibitory control. Indeed, although the neuroplasticity intervention positively influenced perceived control, error perception and perceived competence, only the latter variable appears to be linked to a change in brain activity. Therefore, teaching neuroplasticity could lead students to perceive themselves as more competent, and this change in their perception might prompt them to exert greater cognitive effort and pay closer attention to relevant elements in counterintuitive situations, thereby enhancing activation of their VLPPFC. Interestingly, it was the change in participants' perceived competence between pretest and posttest that was linked to greater inhibitory control-related brain activity, suggesting that this greater brain activity was not due to an already high perceived competence at baseline. Thus, it may be more specifically the interventions that increase the student's perceived competence that led to positive effects, rather than the perception of their skills' malleability, their perceived control and their error perception. Paradoxically, the heart of mindset theory lies more in the belief that it is possible to improve, rather than in the belief that one is competent.

The present results therefore support a tentative but relatively well-documented explanation for the inconsistent results associated with mindset theory, namely that one of the moderating variables between an intervention aimed at inducing a growth mindset and various variables associated with success would be more specifically that of perceived competence. Although the intervention in the present research also had a positive and significant effect on perceived control and error perception, these variables, along with the perception of skills' malleability, would then perhaps instead form part of the confounding variables that induce unexplained variance in the results of research aimed at assessing effects on goal-directed behaviors and academic outcomes. Perceived competence might even be the main variable producing an effect, i.e., a mediating variable (explaining how or why the effect occurs) rather than a moderating variable (specifying when the effect occurs) [91], and mindset-type interventions might be just one way of influencing perceived competence. Of course, these interpretations must be treated with great caution; future research will certainly need to replicate these results. Nevertheless, a number of studies have already shown that perceived competence seems to be related, more than mindset, to variables that mindset is presumed to impact, such as learning goals (as opposed to performance goals) [36,92], goal-directed behaviors [37,38] and performance [36–38].

4.5. Implications for education

The results of the present research are important because they show that teaching the concept of neuroplasticity to participants in the experimental group significantly improved their motivation (perceived control, error perception and perceived competence) and their brain activity related to inhibitory control, compared with participants in the control group. These effects on motivation are interesting in themselves. Indeed, it doesn't seem necessary to deploy long and costly pedagogical resources to induce in students a sense of control over their learning and a more positive view of error, in addition to enabling them to feel more competent, although caution is needed, since it remains uncertain

whether the effects persist over time. These effects can nevertheless be expected to be beneficial, for example in terms of the anxiety felt by some students [93], or well-being more generally [46,94]. However, the effects observed on perceived competence allow to go further: teaching neuroplasticity would enable students to feel more competent, more able to perform the tasks proposed, and this change in their perception would encourage them to activate more brain regions linked to attention and inhibitory control.

Therefore, interventions aiming at inducing a growth mindset may sometimes have positive impacts not because they help induce a growth mindset (which is not always the case), but more specifically because they help increase students' perceived competence. Indeed, these interventions regularly include more than the notion of brain plasticity alone, adding encouragement of various strategies: practicing, making efforts, paying attention to mistakes, etc. In the present research, we focused on these strategies while also incorporating a segment designed to convince students of their ability to succeed at the proposed tasks, directly targeting their perceived competence. Researchers and educational professionals would therefore probably benefit from including in their interventions not only the notion of neuroplasticity, but also the encouragement of relevant strategies. Above all, it appears essential to instill in students the belief that they can accomplish the tasks set before them.

Of course, in this research, the effects of teaching neuroplasticity on the mobilization of inhibitory control appear to be modest, as these effects were not substantial enough to be observed behaviorally. Nevertheless, it represents a positive development: a brief 5-minute video session could potentially modify students' brain activity, prompting a greater engagement of regions critical for attention and inhibitory control. Indeed, this supports the growing body of literature suggesting that teachers can influence their students' brain functioning through the pedagogical choices they make [90,95]. This result on the mobilization of brain mechanisms related to inhibitory control therefore appears substantial, considering that research aimed at evaluating the impacts of inhibitory control training in a general way (domain-general) has shown little hope, with transfer being difficult to achieve [96]. Indeed, it seems more possible to improve inhibitory control skills in a specific task (domain-specific), than to improve them in a general way [96]. However, the intervention designed to promote the mobilization of inhibitory control in the present research is rather general in nature, in that it did not target a specific task, and still seems to have had positive effects on the mobilization of inhibitory control, albeit modest. This is therefore

an important finding, considering all the research highlighting the fundamental role of inhibitory control in mathematics learning in particular [6100–103] and in development and learning in general [4, 16,104–108].

The results of the present research therefore partly support the motivational model presented in the Introduction section (see Fig. 1), without, of course, being able to fully confirm it. Indeed, it is the perceived competence that appears to be the most directly linked variable to the student's cost/benefit analysis and goal-directed behaviors. Perceptions of skills' malleability, control and error may have some role in the interaction of motivational beliefs, since they are related, but probably influence the cost/benefit analysis and goal-directed behaviors less directly than perceived competence. These results hence mainly emphasize perceived competence as a particularly important variable in the cost/benefit analysis, offering a valuable complement to the EVC theory, which already holds strong predictive power [44]. The integration of various motivational theories into this model, along with the findings of the present study, opens the door to more refined and focused research avenues in the future. Fig. 6 restates the concepts of the motivational model presented in the Introduction section, but highlights the relationships supported by the results of the present research. Full arrows represent relationships supported by the present research, while dotted arrows represent those not supported by our results. Grey arrows indicate presumed relationships that were not tested in the present research.

It is obviously not possible to transpose these results directly to the classroom, but it is possible that classroom viewing of the video created in this project (freely available at <http://www.labneuroeducation.org/cerveau>) might have similar effects on motivation and mobilization of inhibitory control in students. Although it is possible that the effects fade over time, a real classroom context could also potentially amplify the effects of the intervention. In a classroom context, a teacher may decide to show the video, but also to pause it to discuss it in greater depth with his or her students. For example, students may be invited to share anecdotes from their own success stories. The video can then be viewed again during the year to provide an opportunity for repetition and thus reinforce the neural networks associated with the notions presented, the notion of learning being inseparable from the notion of repetition [58]. Furthermore, even outside the video presentation, the teacher can continue to reinforce these notions in his or her teaching, without this representing a significant workload. Indeed, it's possible to provide students with short daily comments to the effect that their

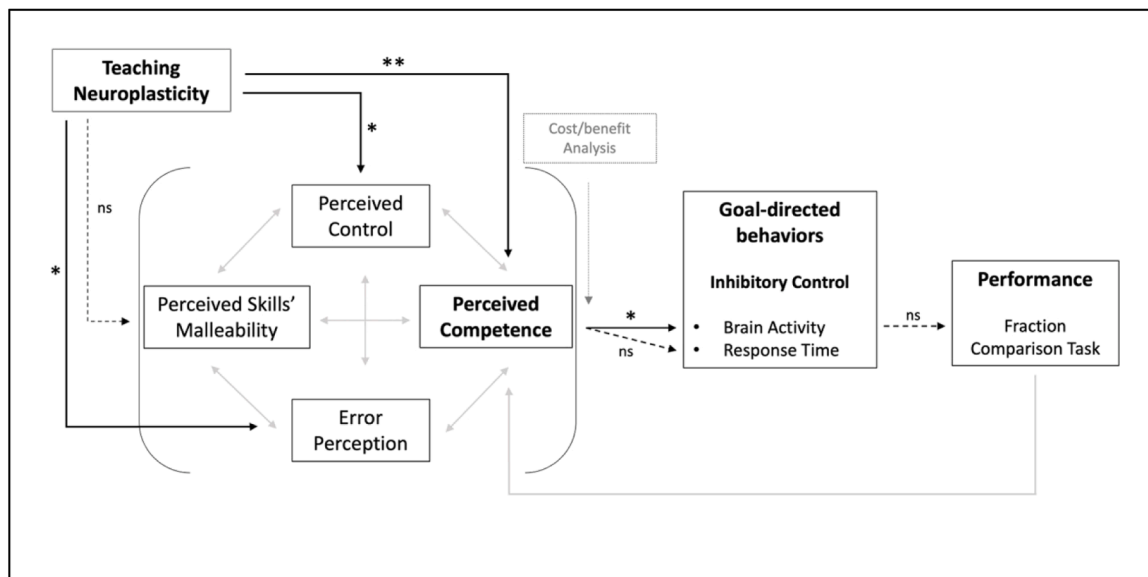


Fig. 6. Model illustrating the relationships supported by the results of this research. * $p < .05$, ** $p < .01$.

neural connections are strengthened when they practice this or that exercise, when they pay attention, apply themselves and put in effort, and when they believe in their abilities. As a matter of fact, a growing body of research shows that interventions aimed at inducing a growth mindset are most effective when the classroom climate is consistent with and supportive of this ideology, particularly when the teacher provides feedback consistent with this mindset [109–111]. The effects of such teaching could therefore be even more beneficial in the classroom, especially as several studies argue that interventions aimed at improving executive functions are more likely to be effective in the context in which they are to be applied, rather than in the laboratory [96]. This ties in with the aforementioned idea that domain-general interventions are generally less effective than domain-specific ones. Thus, a teacher could also use the video to make specific links with different tasks. For example, when evoking a strategy in the video, they could discuss with students how to apply this strategy in the context of comparing fractions, in order to facilitate transfer. Of course, the difficulties students encounter with fractions are not all exclusively related to inhibitory control. Some researchers [97] suggest that these challenges may be linked to the fact that understanding the concept of a fraction is, by nature, complex—particularly because a fraction is composed of two whole numbers rather than just one—and requires the understanding of several sub-concepts: part-whole, ratio, operator, division, and measurement. The integrated theory of numerical development also posits that the consolidation of several more basic mathematical skills, which are prerequisites for understanding fractions, such as understanding numerical magnitude and whole number knowledge, can support better fraction learning [98–100]. That being said, a widely documented difficulty inherent to the concept of fractions lies in the fact that the properties of rational numbers (such as fractions) differ from those of natural numbers (i.e., whole numbers greater than or equal to zero), which requires the mobilization of inhibitory control [11].”

It therefore seems that it is more beneficial to devote energy and teaching resources, however modest, to fostering students’ perceived competence (or self-efficacy), rather than simply focusing on perceived skills’ malleability, the core of mindset theory, or perceptions of control and error. We can then attempt to identify other ways of influencing perceived competence more specifically, without requiring considerable resources. Indeed, the main source for influencing the perception of competence would be personal experience [46,112]. In other words, a student evaluates his own competence in a context by referring mainly to similar experiences he has had. If he has succeeded in most similar situations, his perceived competence will be higher than if the similar situations experienced were unsuccessful. In fact, some researchers argue that success has a greater impact on motivation (particularly perceived competence) than motivation on success [113], although both relationships seem to exist [46]. Thus, one of the most interesting avenues for fostering motivation in students, and more specifically perceived competence, would be to have them experience success. In Fig. 6, this is represented by the arrow from performance to perceived competence. To place students in a situation of success, they need to be offered tasks that present a challenge adapted to their level of competence. The literature on this subject is not new, as seen in the notion of optimal challenge or flow within a more motivational framework [46], or the zone of proximal development suggested by Vygotski as early as 1934 [114]. The underlying idea is simple: offering students tasks that are too challenging for their skill level is likely to provoke anxiety, helplessness [46,115] and cognitive overload, a state in which working memory can no longer process information [116]. Conversely, proposing challenges that are too easy for students’ skill level does not allow them to learn much, in addition to boring them and undermining their motivation [46]. It’s therefore a matter of finding the right balance in the tasks proposed to students, so that the challenge offered is reasonable and falls within the desirable zone: neither too easy nor too difficult. Thus, having students experience successes is one way to influence their perceived competence, but other researchers could also work on

identifying other, short and simple ways to do this.

4.6. Limitations and future directions

The main limitation of this study probably concerns the sample recruited, possibly due, at least in part, to the use of social media, which may have exacerbated a social desirability bias. Initially, it was planned to recruit students with a low success rate on fraction comparison items in the pre-selection questionnaire, in addition to presenting a fixed mindset (low motivational beliefs on the new questionnaire). However, since it was not possible to recruit participants who met these criteria, we had to broaden them. As a result, the participants were initially quite motivated (with a rather growth mindset) and competent in fraction comparison, leading to a non-negligible ceiling effect in both the motivational questionnaire and the fraction comparison task. Leaving little room for improvement, the results may well have been limited by this effect. Research aiming at replicating these results could therefore attempt to recruit a sample more in line with the original target sample: students who are less motivated, or having a lower perception of their competence, in addition to having more difficulty in tasks requiring inhibitory control. The age of participants may also have been a limitation regarding inhibitory control results. Indeed, authors have highlighted that it is not uncommon to observe poor neuroimaging results when attempting to measure inhibitory control in children [117]. As the formation of neural networks related to inhibitory control develops later in life (adult-like networks develop more towards the end of childhood, until the late twenties [117]), this may help explain the lack of statistical power of our brain results with our sample of 10–12-year-old children. It would therefore be particularly interesting to study this phenomenon developmentally, by observing the effects on younger and older children, and on adults.

Another limitation concerns the experimental intervention, which was short (5 minutes) and rather passive; participants were mainly required to watch the video, although it was viewed twice and were asked to summarize it and to answer three comprehension questions afterwards. The short duration and low level of interactivity may therefore have limited the intervention’s impact. A longer, more interactive intervention, e.g. by discussing the concepts presented in greater depth, or by asking participants to write a letter to a friend explaining what they had just learned (referring to the saying-is-believing effect, [118]) would possibly have a greater impact. Considering the limited change in skills’ malleability perception, further research could also explore whether modifications are necessary to address this concept more directly in the video. Moreover, since no delayed post-test was conducted, it remains uncertain whether the effects persist over time. Long-term follow-up would help determine whether these effects are stable or if additional resources are necessary to sustain them. Furthermore, the motivational questionnaire used in this research, although developed and validated to address the many limitations of mindset questionnaires used in previous studies, inevitably has some limitations as well, such as a strong ceiling effect. This ceiling effect is often observed in the results of mindset questionnaires, probably due to the presence of a social desirability bias, considering that students are often told that effort is required or that they can learn from their mistakes. Thus, future research could, for example, attempt to develop a motivational questionnaire that minimizes this ceiling effect, perhaps by framing statements more indirectly in order to avoid social desirability bias as much as possible (e.g., “When I’m told that my mistakes help me improve, I don’t really believe it.”). In parallel, it would also be interesting to develop motivational questionnaires for other disciplines, since this one refers only to mathematics, and that students may have different perceptions in different fields.

The fraction comparison task aimed to isolate, at best, the automatism linked to the *natural number bias*, according to which the digits composing the fraction are interpreted independently, thus leading to the belief that larger digits mean a greater value of the fraction.

However, although this automatism is widely present in students of this age (e.g., [7]), different strategies could still be used to assess the magnitude of fractions, as was the case in the "without common component" conditions, which we had to remove due to the too low presence of the automatism studied. Moreover, the exclusion of these conditions reduced the number of items in the task by a non-negligible half, necessarily resulting in much lower statistical power. At the cerebral level, this may help explain why results related to the ventrolateral prefrontal cortex do not reach the corrected threshold in the whole-brain analysis. The small number of items, combined with the modest sample size, could also contribute to explain the absence of significant differences between groups at the behavioral level. A further limitation of this fraction comparison task is the unexpected ease with which participants performed it. Although the task was designed based on previous studies with participants of the same age group, participants in the present study reported higher success rates and shorter response times than expected (e.g., participants in the study by Gómez et al. [7] responded in 2 to 3.5 s, whereas participants in the present study responded in 1 to 2.8 s). This too-low level of difficulty led to a ceiling effect in the data, which may have limited the observation of differences between the groups. Focusing exclusively on Conditions 1 and 2 may also have contributed to this ceiling effect, as items with a common component tend to be easier. Thus, designing a similar task, but optimized to better match the skills of the sample and to better isolate the automatism, both with *and* without a common component, would also be relevant. It would also have been interesting to assess the effects of the intervention using a more straightforward inhibition task—one that does not involve additional mathematical processing—in order to isolate inhibitory control more directly.

Finally, one of the central questions raised by the results of the present study is that of moderating variables between a neuroplasticity intervention and positive effects on goal-directed behaviors and performance. Future research should certainly attempt to clarify these variables, particularly by deepening our understanding of the role of perceived competence, in addition to targeting other variables potentially at play. Moreover, as the role of perceived competence in this phenomenon seems to have been relatively well documented to date, further research could look at other ways of fostering this perception of competence in students. As mentioned in the section on pedagogical implications, a more systematic study of the effects of interventions specifically aimed at improving perceived competence [92], such as the effects of activities offering a challenge adapted to the students' level of competence in order to make them experience success and thus improve their perceived competence, would therefore be particularly relevant.

5. Conclusion

This research shows that a brief intervention aiming at teaching neuroplasticity can significantly increase students' motivation, in addition to promoting the activation of brain regions important for learning: those linked to inhibitory control. However, the effect does not appear to have been sufficient for participants to complete the implementation of inhibitory control, and this is reflected in reaction times and accuracy on the fraction comparison task. Furthermore, this research not only documents the effects of teaching neuroplasticity, but also provides a better understanding of why and how such an intervention leads to positive effects on brain activity related to inhibitory control. Indeed, perceived competence seems to play an important role in this relationship, being the only motivational variable significantly correlated to brain activity. These results, although modest and only observed for the first time, already shed light on the relevance of introducing neuroplasticity teaching in schools in the form of a short,

simple and inexpensive intervention. This intervention certainly offers an interesting cost-benefit ratio, since in addition to fostering student motivation, it seems to promote brain activity associated with the mobilization of inhibitory control during a difficult and counterintuitive task. These results also point to future avenues of research concerning this type of intervention, aiming at equipping teachers and future teachers to more effectively support students who struggle with the mobilization of inhibitory control.

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Ethics approval

This study was performed in line with the principles of the Declaration of Helsinki. Approval was granted by the by the *Comité d'éthique de la recherche vieillissement-neuroimagerie* (no CER VN 19-20-25) of the CRIUGM.

Consent

Written informed consent was obtained from the parents of the participants.

Data availability statement

The behavioral data supporting the conclusions of this article will be made available by the authors on request. Neuroimaging data cannot be shared due to ethical restrictions.

CRediT authorship contribution statement

Jérémie Blanchette Sarrasin: Writing – review & editing, Writing – original draft, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Martin Riopel:** Writing – review & editing, Validation, Supervision, Methodology, Formal analysis, Conceptualization. **Geneviève Allaire-Duquette:** Writing – review & editing, Visualization, Validation, Supervision, Software, Methodology, Formal analysis. **Sophie McMullin:** Writing – review & editing, Methodology, Investigation, Data curation, Conceptualization. **Élisabeth Bélanger:** Writing – review & editing, Methodology, Investigation, Data curation. **Lorie-Marlene Brault Foisy:** Writing – review & editing, Validation, Supervision, Methodology, Investigation, Conceptualization. **Steve Masson:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

None.

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Supplementary materials

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Appendix A

English translation of the motivational questionnaire

For each statement, circle the number that best describes what you think.

Statements	Strongly disagree	Disagree	Some-what disagree	Some-what agree	Agree	Strongly agree
1. I can't really change my math skills.	1	2	3	4	5	6
2. Whether or not I am good at math, I can always become better.	1	2	3	4	5	6
3. My math skills can't really improve.	1	2	3	4	5	6
4. My math skills can always be improved.	1	2	3	4	5	6
5. With practice, I can get better at math.	1	2	3	4	5	6
6. If I make efforts in math, I'll improve.	1	2	3	4	5	6
7. If I use good strategies, I'll be able to do well in math.	1	2	3	4	5	6
8. My mistakes in math are useful because they help me improve.	1	2	3	4	5	6
9. When I have difficulty in a math exercise, I can still manage to succeed.	1	2	3	4	5	6
10. When I make mistakes in math, I learn from them.	1	2	3	4	5	6
11. I'm good at math.	1	2	3	4	5	6
12. I have trouble understanding anything to do with mathematics.	1	2	3	4	5	6
13. I'm one of the best in mathematics in my class.	1	2	3	4	5	6
14. Compared to the other students in my class, I'm not very good at math.	1	2	3	4	5	6
15. I think I'll do very well in math this year.	1	2	3	4	5	6
16. I'm not very good at learning new things in mathematics.	1	2	3	4	5	6
17. I understand mathematics easily.	1	2	3	4	5	6

Appendix B

Task stimuli

Conditions used for analysis.

Condition 1		Condition 2	
Intuitive with common component		Couterintuitive with common component	
5/9	7/9	4/9	4/5
8/11	6/11	2/5	2/9
5/12	7/12	5/7	5/13
3/7	1/7	3/5	3/8
2/5	3/5	7/16	7/9
13/14	9/14	8/9	8/13
3/8	5/8	9/14	9/11
11/13	8/13	10/13	10/17
14/17	10/17	11/16	11/13
3/11	5/11	1/3	1/9
2/7	4/7	4/9	4/15
7/9	4/9	5/8	5/14

Conditions excluded from analysis.

Condition 3		Condition 4	
Intuitive without common component		Couterintuitive without common component	
4/7	1/3	8/15	5/6
3/14	9/17	4/5	6/13
9/16	1/3	5/17	2/3
3/5	11/13	3/4	6/13
11/15	4/9	5/8	7/15
2/3	6/7	6/13	4/5
5/12	1/6	5/6	7/12
4/9	11/16	8/15	7/9
7/12	2/5	3/5	5/14
1/6	3/7	5/9	3/4
5/9	2/7	5/7	6/11
3/8	9/14	3/5	4/9

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