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ASSOCIATION POUR LA RECHERCHE EN NEUROÉDUCATION / ASSOCIATION FOR RESEARCH IN NEUROEDUCATION

NEUROEDUCATION
2014 – Volume 3, Number 1

EXPERIMENTAL RESEARCH

Involvement of inhibitory control mechanisms in overcoming intuitive interference

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ABSTRACT

Many students encounter difficulties in science and mathematics that may stem from intuitive interference of salient irrelevant variables. We focused on the comparison of perimeters task, in which area is the irrelevant salient variable. In congruent trials (no interference), accuracy is higher and reaction time is shorter than in incongruent trials (area variable interference). A brain-imaging study related to this task indicated that correctly answering the incongruent condition is associated with activation in prefrontal brain regions known for their executive inhibitory control. In the current study we explored the relationship between inhibitory control mechanisms and the ability to overcome intuitive interference. Participants in the study were 90 ninth graders. The efficiency of their inhibitory control mechanisms was assessed and accuracy and reaction time of correct responses in the comparison of perimeters task were recorded. The findings indicate that students with efficient inhibitory control mechanisms scored significantly better in the incongruent conditions than did those with inefficient ones. In addition, the findings indicate that the higher the efficiency of inhibitory control mechanisms, the better students were in overcoming the intuitive interference. These findings indicate the importance of inhibitory control mechanisms in overcoming interference in science and mathematics. They point to the possibility of improving students' ability to overcome intuitive interference by strengthening their inhibitory control mechanisms. We also demonstrate that applying cognitive psychology and neuroscience methodologies in science and mathematics education research contributes to both fields.

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To cite this article: Babai, R., Younis, N., & Stavy, R. (2014). Involvement of inhibitory control mechanisms in overcoming intuitive interference. *Neuroeducation*, 3(1), 1-9. https://doi.org/10.24046/neuroed.20140301.1

Received October 14, 2014. Received in revised form December 16, 2014.
Accepted in January 12, 2015. Available online March 6, 2015.
Neuroeducation, 3(1), 1-8
ISSN: 1929-1833

1. Introduction

It is well known that many students encounter difficulties in science and mathematics (e.g., TIMSS or PISA studies: Martin, Mullis, Foy, & Stanco, 2012; Mullis, Martin, Foy, & Arora, 2012; OECD, 2014). Numerous studies have been carried out to understand students' conceptions and reasoning. The underlying assumption is that understanding students' reasoning in science and mathematics will improve teaching in these domains.

Several approaches to explain students' difficulties have been developed. One argues that incorrect responses result from lack of required cognitive schemes (e.g., Piaget & Inhelder, 1974). Another view is that students bring alternative, internally coherent, robust, and persistent conceptions to learning situations (e.g., Driver et al., 1994; Vosniadou & Ioannides, 1998). A third approach identifies two distinct types of reasoning processes: formal/logical and intuitive (e.g., Evans & Over, 1996; Tversky & Kahneman, 1983).

We believe that many students' difficulties stem from interference of a salient irrelevant variable with formal/logical reasoning (Stavy & Tirosh, 2000). Apparently, certain variables of the task are so salient that they are automatically processed and thus interfere with correct reasoning. This interference is reflected in students' erroneous responses, even when they have the knowledge and skills to solve these tasks correctly.

Let's consider the following examples showing interference of salient irrelevant variables in different content domains.

1.1 *Example from Physics*

Two matchboxes, one full of sand and the other empty, are held at the same height (see Figure 1). They are both dropped at the same time in a vacuum. Students were asked: Will the matchboxes hit the ground at the same time? If not, which will hit the ground first?

Many students, including about 80% of first year university physics students, answered incorrectly that the heavier box would hit the ground first (Champagne, Klopfer, & Anderson, 1979). According to physics laws, the two boxes will hit the ground at the same time. In this task, the interfering variable is the *weight* of the boxes.

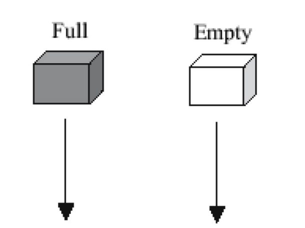

Figure 1. Free fall task.

1.2 Example from Biology

Tick the correct answer.

The size of a lion's liver cell is

☐ smaller than

☐ equal to

☐ larger than

the size of a cat's liver cell?

Seventy-five percent of students in Grade 8 incorrectly answered that the lion's liver cell is larger, since the lion is "bigger" than the cat (Tirosh & Stavy, 1999). The correct response to this task is "equal to." In fact, most cells of most organisms are approximately equal in their diameter (McMahon & Bonner, 1983). In this task, the interfering variable is the *size* of the animal.

1.3 *Example from Probability*

Two bags have black and white balls (see Figure 2).

Bag A: 6 black balls and 4 white balls

Bag B: 3 black balls and 2 white balls

Which bag gives a better chance of picking a black ball?

☐ Same chance

☐ Bag A

☐ Bag B

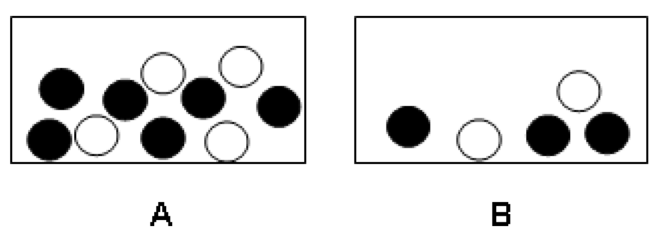

Figure 2. Probability task.

In Green's (1983) study, about 50% of adolescents incorrectly answered that Bag A gives a better chance of picking a black ball, since "it contains more black balls." The correct response to this task is "same chance," as the ratios of number of black balls to number of white balls in each box are equal. In this task, the interfering variable is the *number* of black balls.

1.4 Example from Geometry

Students were presented with these two shapes (Figure 3) and were asked to compare their perimeters (Stavy & Tirosh, 2000).

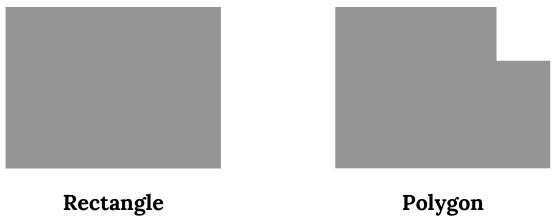

Figure 3. Comparison of perimeters task.

About 70% of students in Grades 1-9 incorrectly answered that the perimeter of the rectangle was larger because "it is larger" or "it has larger area" (Stavy & Tirosh, 2000).

The correct response in this task is that the perimeters of both shapes are equal. In this task, the interfering variable is the *area* of the shapes.

In general, when students are presented with two objects that differ in a salient quantity A (automatically, intuitively processed) and are asked to compare the objects with respect to another quantity B, they tend to respond according to the salient quantity A: larger A -- larger B. In daily life such intuitive responses are often correct. However, in many cases these responses contradict normative reasoning in science and mathematics, leading to incorrect judgments.

In order to unveil the reasoning processes associated with intuitive interference and how we overcome it, we and other research groups have recently started employing cognitive psychology and neuroscience methodologies, such as reaction time and brain imaging (e.g., Dunbar, Fugelsang, & Stein, 2007; Masson, Potvin, Riopel, & Foisy, 2014; Stavy, Goel, Critchley, & Dolan, 2006). We believe that employing these methodologies can contribute to a better understanding of students' difficulties and reasoning processes, and hence to improvements in science and mathematics education.

Reaction time is one of the most widely used methodologies in cognitive psychology. It is the time interval between the presentation of a task and the response. It is widely accepted that the length of reaction time gives an indication of the amount of neural processing that occurs while solving the task (Brebner & Welford, 1980; Viggiano, 1999). A more complex reasoning process is expected to take longer. We used reaction time methodology to better understand the nature of intuitive interference. As a model system, we studied the comparison of perimeters task described above. This task allows manipulations of the variables and design of task conditions with or without interference, unlike many tasks in the domain of science.

In previous studies participants were asked to compare the perimeters of pairs of shapes (see Figure 4). In some of the pairs there was no interference of the salient variable (congruent condition), and in others there was interference of the salient variable (incongruent conditions):

Congruent -- no intuitive interference, as one shape has a larger area and a longer perimeter than the other shape.

Incongruent -- there is intuitive interference, as one shape has a larger area, but not a longer perimeter. Incongruent inverse: One shape has a larger area but a shorter perimeter. Incongruent equal: One shape has a larger area but the perimeters are equal.

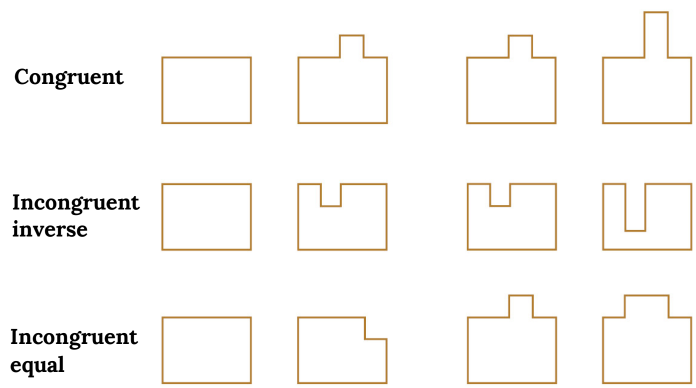

Figure 4. Examples of congruent, incongruent inverse, and incongruent equal task conditions.

When schoolchildren, adolescents, and adults have been asked to compare the perimeters of the shapes, it has been consistently found that in the congruent condition accuracy was significantly higher and reaction time for correct responses significantly shorter than in the incongruent conditions. In addition, in most studies it has been found that the incongruent equal condition yielded a lower rate of success and a longer reaction time for correct responses than did the incongruent inverse one (e.g., Babai, Levyadun, Stavy, & Tirosh, 2006; Babai, Nattiv, & Stavy, 2014; Babai, Shalev, & Stavy, 2014; Babai, Zilber, Stavy, & Tirosh, 2010; Stavy & Babai, 2008). When participants were asked to compare the areas of the shapes, almost all of the responses were correct and relatively fast (significantly faster than for perimeters comparison) in all conditions (e.g., Babai *et al.*, 2006; Babai *et al.*, 2010). These findings support our conjecture that area is indeed the salient variable in this task and that participants have difficulty in ignoring it when comparing perimeters.

These findings were explained as follows:

In the congruent condition the processing of area and perimeter result in the same conclusion (no interference); this is the end of the processing and participants respond correctly and fast. In the incongruent conditions the results of these two streams of processing reach conflicting results, one based on the area comparison and the other on perimeter comparison. This conflict must be resolved, either by overcoming the intuitive interference, a demanding and time-consuming process, or by giving an incorrect response (Stavy *et al.*, 2006).

Having noted the robust behavioral data related to intuitive interference in the comparison of perimeters task, Stavy and her colleagues set out to determine the neural basis of this behavior through brain imaging. Functional magnetic resonance imaging (fMRI) allows researchers to determine which brain areas are activated when participants perform different types of mental activity. Regarding the comparison of perimeters task we asked: Will the congruent condition specifically activate different brain areas than will the incongruent one? And in addition, will the incongruent condition specifically activate different brain areas than will the congruent one? If so, could these findings suggest what types of mental activities are specifically performed in each condition?

For this purpose, an fMRI study was conducted with adult participants using congruent and incongruent equal conditions (see Figure 4). Participants were asked to compare the perimeters of the shapes. Accuracy of responses, reaction time, and brain activity were recorded (Stavy *et al.*, 2006; Stavy & Babai, 2010).

As expected, significant effect of congruity was found for accuracy as well as for reaction time of correct responses. Accuracy was higher and reaction time for correct responses was shorter in the congruent condition.

To determine which brain regions are specifically activated in the congruent condition, we compared brain activity during correct responses for congruent trials with brain activity during correct responses for incongruent trials. Enhanced activity was observed in bilateral parietal areas known to be involved in perceptual and spatial processing, including processing related to comparison of quantities such as found in our task (e.g., Fias, Lammertyn, Reynvoet, Dupont, & Orban, 2003; Pinel, Piazza, Le Bihan, & Dehaene, 2004). This activation is likely to reflect the automatic processing of the intuitive variable area.

To determine which brain regions are specifically activated in the incongruent condition, we compared brain activity during correct responses for incongruent trials with brain activity during correct responses for congruent trials. Enhanced activity was observed in bilateral prefrontal areas in association with overcoming the intuitive interference in incongruent trials. These brain areas are known for their executive inhibitory control over other posterior brain regions during processing of different cognitive functions (e.g., Aron, Robbins, & Poldrack, 2004; Stavy & Babai, 2010; Stavy *et al.*, 2006). This activity is likely to reflect the inhibition of the processing of the irrelevant variable area.

In addition, findings of the brain-imaging study have shown that the same bilateral parietal brain regions that were specifically activated in the congruent condition were also activated when intuitively incorrectly answering the incongruent condition as compared with correctly answering this condition. Moreover, the same bilateral prefrontal brain regions that were specifically activated in the incongruent condition (versus the congruent one) were also activated when overcoming the intuitive interference and correctly answering the incongruent condition as compared with intuitively incorrectly answering this condition.

The brain-imaging study showed that different brain areas are activated when there is no interference and when overcoming the interference, although participants are not aware of the condition (congruent or incongruent). During responses to congruent trials, parietal regions related to comparison of quantities are activated. This activation is likely to reflect the automatic processing of quantities (Stavy *et al.*, 2006). During correct responses to incongruent trials, prefrontal brain areas related to executive inhibitory control are activated.

The findings described above suggest that control mechanisms play an important role in overcoming intuitive interference. These findings conform with previous suggestions that reasoning biases stem from the failure of control mechanisms in the reasoning process and not necessarily from a lack of relevant knowledge or lack of logical schemes (Dempster & Corkill, 1999; Houdé & Guichart, 2001; Moutier, Angeard, & Houdé, 2002; Moutier & Houdé, 2003).

In the current paper we further explored the relationship between inhibitory control mechanisms and the ability to overcome intuitive interference in the comparison of perimeters task. We describe an experiment aimed at finding out whether students who exhibit efficient inhibitory control mechanisms will succeed better in overcoming intuitive interference than those who exhibit inefficient ones.

2. Methodology

2.1 Participants

Participants in the study were 90 ninth graders from the same school in central Israel.

2.2 Digit cancellation test

The efficiency of inhibitory control mechanisms of each student was assessed using the digit cancellation test (Lezak, Howieson, & Loring, 2004) according to Israeli research norms of age and gender determined and reported by Vakil and his colleagues (Vakil, Blachstein, Sheinman, & Greenstein, 2008). In this test participants were shown a pattern of digits printed on a page in an organized pattern (in rows, just as in reading). They were asked in the first stage to scan the organized pattern of digits and to cross out target digit "8". In the second stage they were asked to scan the organized pattern of digits and to cross out the target digits "3" and "5." Time to completion of the task in each stage and the number of errors in each stage were measured. According to the Israeli research norms for gender and age (Vakil *et al.*, 2008) students with below average reaction times in each stage, number of errors in each stage, differences in reaction times between stages, and differences in number of errors between stages were classified as having efficient inhibitory control mechanisms. Students with average and above average scores were classified as having inefficient inhibitory control mechanisms.

2.3 Comparison of perimeters computerized test

Each student was individually presented with a computerized comparison of perimeters test. In each test trial, two shapes were presented, and the students were asked to compare the perimeters of the two shapes, i.e., to judge whether the right shape had a larger perimeter, the left shape had a larger perimeter, or the two shapes had equal perimeters. Each trial was presented on the screen until the participant responded: "left shape" by pressing the F-key, "right shape" by pressing the J-key, or "equal perimeters" by pressing the space bar. The students were asked to answer correctly and as quickly as they could. Accuracy and reaction time of each response were recorded.

The test included 16 congruent, 16 incongruent inverse, and 16 incongruent equal trials (see Figure 4). The trials were presented in pseudorandom order with the following constraints: (1) the same type of response (right shape is larger, left shape is larger, equal perimeters) did not appear in more than two consecutive trials; (2) the same type of condition (congruent, incongruent inverse, incongruent equal) did not appear in more than two consecutive trials.

The test session started with instructions as described above, followed by 6 training trials, 2 from each condition (different from the ones presented in the test) for practice with the task and the experimental setting.

2.4 Analysis of the data

For each student we calculated the percentage of correct responses for each condition and the median reaction time for correct responses for each condition. Repeated measure General Linear Model (GLM) and Bonferroni post hoc tests were carried out in SPSS software in order to detect significant differences between conditions and between the two groups of students with efficient and inefficient inhibitory control mechanisms. Moreover, Pearson correlation was used to determine correlation between level of efficiency of inhibitory control mechanisms and performance in the incongruent comparison of perimeters task conditions.

3. Results

3.1 Accuracy and reaction time of correct responses for the entire population

The results of accuracy and reaction time for correct responses in the comparison of perimeters computerized test for the entire population (N=90) are presented in Table 1.

Table 1. Mean accuracy and reaction time for correct responses and their SEM in the comparison of perimeters test for the entire population (N=90).

Condition	Accuracy (%) [SEM]	Reaction time in ms [SEM]
Congruent	94.0 [1.2]	1325 [45]
Incongruent inverse	62.8 [4.3]	2048 [208]
Incongruent equal	21.3 [2.8]	3450 [336]

With respect to accuracy, as expected, there was a significant main effect of congruity with a large effect size (F=341.314, df=88, p<.001, partial eta squared=.886). The congruent condition yielded significantly higher success rate than did the incongruent inverse and the incongruent equal conditions; the incongruent inverse condition yielded a significantly higher success rate than did the incongruent equal one (p<.001 for all comparisons).

Analysis of reaction time for correct responses revealed a significant main effect of congruity with a large effect size (F=24.354, df=45, p<.001, partial eta squared=.520; the analysis included those students, n=47, for whom there was data for reaction time of correct responses in all three conditions). The congruent condition yielded significantly shorter reaction time than did the incongruent inverse condition and the incongruent equal conditions (p=.013 and p<.001 respectively); the incongruent inverse condition yielded a significantly shorter reaction time than did the incongruent equal one (p=.009). These findings are in line with findings obtained in previous studies related to the comparison of perimeters task (e.g., Babai *et al.*, 2006; Babai, Nattiv *et al.*, 2014; Babai, Shalev *et al.*, 2014).

3.2 *Performance of students with efficient and inefficient inhibitory control mechanisms*

In the following section we will compare the performance of students with efficient and inefficient inhibitory control mechanisms. Table 2 depicts accuracy and reaction time for correct responses in the comparison of perimeters computerized test for students with efficient (*n*=44) and inefficient (*n*=46) inhibitory control mechanisms.

Table 2. Mean accuracy and reaction time for correct responses and their SEM in the comparison of perimeters test for students with efficient (n=44) and inefficient (n=46) inhibitory control mechanisms.

Condition	Accuracy (%) [SEM]		Reaction time in ms [SEM]	
	Efficient *n*=44	Inefficient *n*=46	Efficient *n*=44	Inefficient *n*=46
Congruent	98.7 [0.9]	89.5 [2.0]	1404 [76]	1250 [47]
Incongruent inverse	95.0 [1.7]	31.9 [5.1]	1994 [156]	2126 [462]
Incongruent equal	40.1 [4.1]	3.4 [1.2]	3371 [363]	2514 [784]

Analysis of the accuracy results depicted in Table 2 revealed significant difference between the two groups of students with a large effect size (*F*=204.827, *df*=88, *p*<.001, partial eta squared=.699). In addition, a significant interaction between group and congruity was found with a large effect size (*F*=63.996, *df*=87, *p*<.001, partial eta squared=.595). Students with efficient inhibitory control mechanisms outperformed their peers with inefficient inhibitory control mechanisms predominantly in the incongruent conditions. Analysis of reaction time for correct responses (including those students for whom there was data for reaction time of correct responses in all three conditions, efficient: *n*=40; inefficient: *n*=7) did not reveal a significant difference between the two groups of students and there was no significant interaction between group and congruity. Additional analysis of reaction time for correct responses performed separately for each condition did not reveal significant differences between the two groups of students. This analysis included all participants for whom there was data for reaction time of correct responses.

3.3 *Correlation between students' efficiency of inhibitory control mechanisms and success rate*

In order to explore if there was correlation between students' efficiency of inhibitory control mechanisms and rate of success in the incongruent comparison of perimeters test, we used two measures obtained by the digit cancellation test: the differences in the number of errors between the two stages of the test and the differences in reaction times between the two stages of the test. Small differences indicate efficient inhibitory control mechanisms and large differences indicate inefficient ones.

A high and significant reciprocal correlation was found between students' differences in the number of errors between the two stages of the digit cancellation test and success rate in both incongruent inverse and incongruent equal comparison of perimeters conditions (Pearson correlation=-.644 and -.525, respectively, *p*<.001 for both). As seen in Figure 5, students with a lower measure of differences in errors between the two stages of the digit cancellation test, i.e., students with higher efficiency of inhibitory control mechanisms, obtained a higher success rate in each of the incongruent conditions of the comparison of perimeters test.

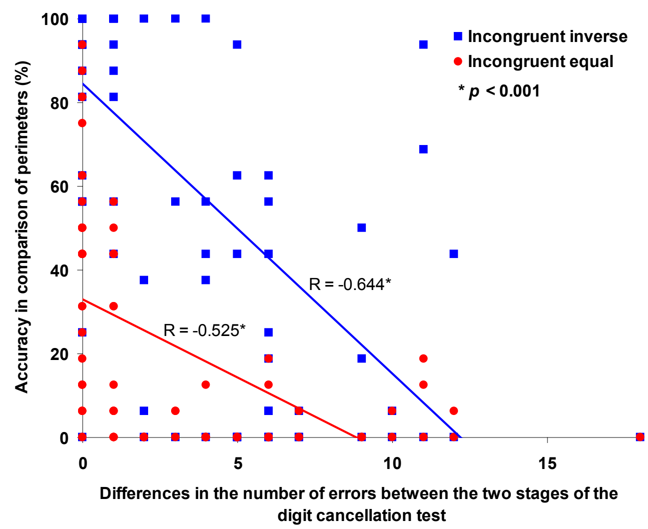

Figure 5. Correlation between accuracy of responses in the incongruent comparison of perimeters conditions and the differences in the number of errors between the two stages of the digit cancellation test.

A high and significant reciprocal correlation was also found between students' differences in reaction times between the two stages of the digit cancellation test and success rate in both incongruent inverse and incongruent equal conditions (Pearson correlation=-.724 and -.688, respectively, *p*<.001 for both). As seen in Figure 6, students with a lower measure of differences in reaction times between the two stages of the digit cancellation test, i.e., students with higher efficiency of inhibitory control mechanisms, obtained a higher success rate in each condition of the comparison of perimeters test.

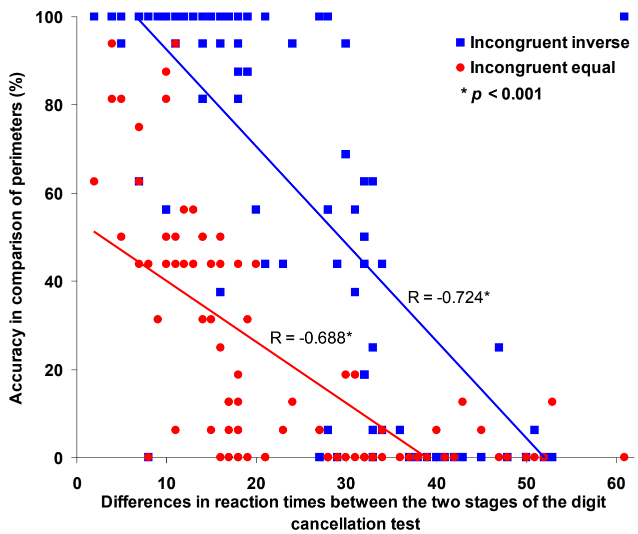

Figure 6. Correlation between accuracy of responses in the incongruent comparison of perimeters conditions and differences in reaction times between the two stages of the digit cancellation test.

4. Discussion

Our objective is to explore how irrelevant salient variables interfere with formal/logical reasoning and how students can overcome this interference. We use several methodologies and different tasks and conditions to explore reasoning processes when there is no interference and when overcoming the intuitive interference (see for example, Babai & Stavy, 2015).

Our studies show that irrelevant salient variables strongly interfere with formal/logical reasoning, leading to difficulties in science and mathematics. This interference is robust, thus leading to a very high percentage of errors. It is evident in different content domains and across different age groups, including adults.

As a model system, we focused on a task in geometry, the comparison of perimeters task. Studies employing cognitive psychology and neuroscience methodologies (reaction time, fMRI) using this task have shown that when participants are correctly responding to incongruent trials, prefrontal brain regions related to inhibitory control mechanisms are activated. These studies have suggested that inhibitory control mechanisms have a key role in overcoming this intuitive interference, as they might inhibit the processing of the salient irrelevant variable and thus prevent its effect. Our goal here was to test this suggestion and directly explore whether students with efficient inhibitory control mechanisms succeed better in overcoming intuitive interference than do their peers with inefficient inhibitory control mechanisms. We used the digit cancellation test in order to assess the level of students' efficiency of inhibitory control mechanisms. It should be noted that, although the test measures inhibitory control mechanisms, students could have scored differently on the digit cancellation test for reasons beyond their inhibition capabilities.

The findings of the current study indicate that students with efficient inhibitory control mechanisms score significantly better in the incongruent conditions of the comparison of perimeters task than do those with inefficient ones (Table 2). In addition, the findings indicate that the higher the efficiency of inhibitory control mechanisms, the better students are in overcoming intuitive interference (Figures 5 and 6). It should be noted that efficient inhibitory control mechanisms are not sufficient in overcoming the intuitive interference in the incongruent equal condition, which is known to be the most difficult condition. It is possible that this condition requires more developed inhibitory control mechanisms or other executive functions. In a previous study we showed that adult participants who were more successful in solving incongruent equal trials had a higher level of activation in the prefrontal brain regions as compared with less successful participants. We suggested that this enhanced activity in the prefrontal regions may be an expression of participants' strong and efficient inhibitory control mechanisms (Stavy & Babai, 2010).

Overall, the findings of the current study indicate that inhibitory control mechanisms play an important role in overcoming intuitive interference in science and mathematics and could explain students' difficulties in these domains. Indeed, a recent intervention study related to the comparison of perimeters task, which strengthened inhibitory control mechanisms through issuing a specific warning, significantly improved students' performance (Babai, Shalev *et al.*, 2014). In view of these findings, we suggest that educators should put more emphasis on enhancing students' inhibitory control mechanisms in addition to supporting relevant content knowledge. Successful attempts to improve executive functions have been carried out mainly with preschoolers (e.g., Diamond, Barnett, Thomas, & Munro, 2007; Rueda, Rothbart, McCandliss, Saccomanno, & Posner, 2005).

The current study also demonstrates that applying cognitive psychology and neuroscience methodologies in science and mathematics education research can contribute to science and mathematics education and to cognitive neuroscience both theoretically and practically. We share with other researchers the belief that construction of direct links between brain data and educational practice is important for both fields (e.g., Grabner & Ansari, 2010; Masson, 2012; Sigman, Pena, Goldin, & Ribeiro, 2014). This requires collaboration among educators, educational researchers, and cognitive neuroscientists.

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