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Can adolescents make better decisions? The answer of Physics Physics as critical thinking training

¿Pueden los adolescentes tomar mejores decisiones? La respuesta de la Física La Física como entrenamiento del pensamiento crítico

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Abstract

To learn Physics is traditionally a difficult task. In the present study we want to infer if there is a relation between a Socratic methodology of teaching Physics and the executive functions of students. 69 undergraduate students who learnt with a Brain-Based Teaching Approach (BBTA) methodology were compared to a sample with the same N who had learnt in a masterclass style. Both groups were analysed through Stroop test in order to find differences in the executive functions, differences in the inhibition of first intuitive response. T-test analysis suggests that there is a notorious difference between both groups ($p<0.036$) in the interference process (Stroop test) and it would imply that this kind of brain-based teaching methodology improves students´ reasoning process, as far as we know the anterior cingulate and the frontal lobe work together in that process. The results of this research suggest that there is an increase of the inhibition related to the way of learning and no difference by sex are shown. To

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learn Physics in the proposed way seems to reinforce the executive functions and the teaching method would be implemented in different science subjects.

Keywords: Stroop interference, inhibition, executive functions, scientific concepts, neuroeducation, Physics education, learning Physics, teaching Physics, Brain-Based Teaching Approach (BBTA), frontal lobe, stem, steam.

Resumen

Tradicionalmente, aprender Física es una tarea complicada. En el presente estudio queremos conocer si existe relación entre el aprendizaje de la Física de modo mayéutico o socrático y las funciones ejecutivas del cerebro. Sesenta y nueve estudiantes preuniversitarios que aprendieron Física empleando un método fundamentado en el funcionamiento del cerebro fueron comparados con un grupo equivalente que aprendió Física empleando la clase magistral. Ambos grupos fueron analizados con el test de Stroop para buscar diferencias en las funciones ejecutivas, más concretamente en la inhibición de las respuestas inmediatas e intuitivas. Se observó diferencias significativas entre ambos grupos ($p<0.036$) en el control de la interferencia o inhibición. Estos resultados podrían indicar que la metodología fundamentada en el funcionamiento del cerebro mejora el proceso de razonamiento de los estudiantes, puesto que sabemos que la cingulada anterior y el lóbulo frontal funcionan como un tándem en ese proceso. Los resultados del presente estudio sugieren una mejora en la inhibición que está relacionada con la forma de aprender. El método propuesto parece que refuerza las funciones ejecutivas del cerebro y tal vez sería posible emplear dicho método en otras asignaturas.

Palabras clave: test Stroop, interferencia, funciones ejecutivas, conceptos científicos, Física, aprendizaje, neuroeducación, enseñanza de la Física, lóbulo frontal, stem, steam.

INTRODUCTION

Several articles indicate preconceptions and misconceptions students have in attending the explanations of natural phenomena: kinetics (Trowbridge & McDermott, 1981), vectors (Aguirre, 1988), dynamics (Clement, 1982), energy and momentum (Lawson *et al.,* 1987). In addition, there is a compilation of common difficulties in learning Physics concepts (Lillian *et al.,* 1999). There is an extensive bibliography about it. Even though these drawbacks are well known, there is a lack of procedures to succeed in the learning process. These procedures don´t seem to be fully developed and they are far from being completely satisfactory.

Redish (1994) and Herrán (2002) indicate that the troubles when learning Physics come from different causes. The problem does not arise due to the country or region of the planet where it is performed but to the inherent study of Physics. This is related to the way the brain acquires new information and learns it, as well as the characteristics of the scientific method of Physics.

The abstraction required (stage of Piaget's formal operations) coincides in adolescence with the period of myelination of the frontal lobe, which is necessary in mature decision-making and the development of executive functions (Kahneman, 2012).

Even with Physics experts, the prefrontal cortex seems to perform an inhibitory role rather than having achieved a reorganization of neural networks (Dunbar, 2009).

Natural phenomena described by Physics implies preconceptions before finding an appropriate formal explanation. The existence of an intuition about physical phenomena related to movement determines a prejudice about the appropriate description of these phenomena.

Anterior cingulate is a section of the brain that is activated specially when contradictory information is shown.

When a student who does not know about formal Physics observes a simulation of a physical phenomenon and it does not agree with what is expected, a great activity in the anterior cingulate is observed, whether the explanation is right or wrong from a physical point of view. If what you see is what you expect to see, the dorsolateral prefrontal cortex is activated, although what is analyzed is not physically possible. However, if the student has formal Physics knowledge and knows the explanation of the phenomenon, the dorsolateral prefrontal cortex is activated, specifically the medial frontal gyrus in both situations, whether what the student sees is physically possible or not, activating also the anterior cingulate when it is not physically correct. This indicates that the frontal lobe must judge (executive functions), which intuitively establishes the limbic system, since it seems to cause an inhibition of the intuitive response to offer the correct response (Petitto *et al.,* 2009).

The student makes mental patterns, maps on which knowledge is shaped and modifying them is complex, laborious and requires time. The way of producing changes in the patterns of understanding closely resembles the paradigm shifts that the History of Science has undergone. This would explain why it is so difficult to learn Physics and internalize it. To overcome these preconceptions, explicit attention is required.

Some authors (Husnaini *et al.,* 2019) recommend a greater presence of experiments that allow the contrast between acquired knowledge and preconceptions to start teaching Physics at educational levels prior to those currently established, with the rigor that corresponds to the age. Likewise, they invite professionals of education to know about the interests of the students to establish affective bonds with the subject.

Whenever we solved a Physics problem, the frontal lobe is activated. Although the brain does not seem to be designed to represent knowledge about Physics, it does seem to be designed to represent knowledge of the physical world, so that linking both representations requires formal teaching (Mason & Just, 2016).

The frontal lobe is in charge of the executive functions of solving a Physics problem, specifically serving as a guide to the appropriate selection of the previously structured knowledge pattern (Bartley *et al.,* 2019). Moreover, the physiological network established in solving the Physics problem is independent, whether the result is correct or not.

The frontal lobe is already activated when we are making decisions in our daily life.

A more or less concious effort is required to learn Physics (Posner, 2009), depending on one's motivation but willpower is necessary.

Building knowledge from what is already known seems to be successful. This point has been proven in learning music process. Daniel Levitin, a renowned neuroscientist dedicated to studying the brain and music, among other great experiments subjected the singer and composer Sting to various tests (National Geographic, 2009) to conclude that the starting point of our preferences begins with something familiar and well liked, combined with an element of novelty. This is the attractive balance that causes one to perceive surprises within what we expect. In other words, we do not have great conflicts in assimilating what is familiar to us, even if it has traces of something new (Levitin, 2006). This strategy seems to be helpful to learn not only music but also Physics.

Each person undergoes the learning process in a unique way since each person's brain is also unique, our personality is unique. One must create his or her own mental models. However, students are unable to do this without the guidance of their mentor, the teacher. This leading figure knows how to guide and take them out of themselves in order to advance in the acquisition of knowledge. Students are required to create their knowledge based on personal experience and the affective bond they generate towards it. Constructivism is not defended here as a form of learning, since the learning process is necessarily linked to the adult.

Current educational proposals on the teaching of Physics

If we understand how the brain works, we can improve the teaching methods.

Learning through brain-based learning strategies implies higher motivations and results in students. Some authors have proposed a theoretical brain-based framework for research in Physics education (Redish, 2003). The Brain-Based Teaching Approach (BBTA) proposed by Caine & Caine (2003) is based on similar principles. Freeman & Wash (2013) offer ten strategies for college teaching and learning and show that teaching with the "brain" in mind is a win-win situation and may increase the academic performance, sharpen the thought processes, and improve the attitudes toward learning of college students. They are more motivated.

The effectiveness of this BBTA learning (Caine & Caine, 2003) has been previously proven, suggesting that the specific results in the teaching of Physics with these techniques offer improvements in the understanding of Newtonian laws (Saleh, 2012).

This teaching approach is effective in yielding a remarkable learning achievement among students. These methodologies imply higher motivations to learn Physics in high school students (Saleh, 2011).

Similar principles have proved that brain-based learning environment has a positive effect on the higher-level learning, retention of the learning and the attitude (Tüfekçi *et al.,* 2009). The same results are obtained by Worden, Hinton, and Fischer (2011). These authors stressed the importance of educators and neuroscientists working together to learn how to teach children more effectively.

Calhoun (2012) makes a direct question: Brain-Based Teaching: Does It Really Work? The answer seems to be very clear. Once again, the results of this study are positive.

Educational intervention proposal

After the theoretical foundation and considering the characteristics of Physics and adolescents, we propose a brain-based methodology.

It implies an holistic point of view, from the unity of knowledge. Necessary relationship between Physics and other branches of knowledge, such as Mathematics, Biology, Philosophy, History (Pettito, 2004), Geography and Music, among others. Transversality is inherent in the process of acquiring knowledge. Linking concepts is easier from analogies even when the students are distracted (Park, 2014).

The main steps are:

Generation of significant knowledge through the affective relationship between the student and the subject (Damasio, 2003). Use of cinema and literature.

The argumentative class incites students to judge and reason, to recognize the value that this knowledge has. Socratic reasoning as a way of learning (Koenig *et al.,* 2007).

Setting up a situation incites further development of problem-solving skills, moving from limiting strategies (writing equations, known or unknown things, or looking for similar examples) to strategies that broaden horizons (diagramming, description of concepts, qualitative analysis, breakdown into sub-problems), so that students are also more motivated by what they are learning (Ogilvie, 2009). Physics novices try to use the equation that best suits the data they have (Docktor *et al.,* 2016). The methodology favors the decision-making processes of the expert.

Experimentation as a Socratic tool (Hake, 1992). students can self-evaluate their work and participate in the qualification of laboratory practices (Bain, 2005) through a rubric.

Labs are important in both student´s motivations and understanding of concepts (Husnaini & Chen, 2019).

This brain-based learning method can be generalized, in so far as we consider the inextricability of Physics from all subjects and its transversality.

Throughout the proposed process, Bloom's taxonomy is followed, respecting and enhancing the unique processes of each student.

The methodology requires the generation of one's own material that includes scenes and simulations or virtual or physical laboratories, so that the student can complement what happens in class with these experiences. These contents use comparisons and analogies to be able to link the new content with what has already been established. In this way, a previous orientation is sought before explaining a new concept in the most enriched posible way but considering the limitations of the comparison, as some authors advise (Körhasan & Hidir, 2019).

From a motivational point of view, the method is based on the expectations that students have about themselves and their future (Vroom, 1964); on the need to achieve goals (McClelland, 1961); on the importance of curiosity (Harlow *et al.,* 1950); on positive reinforcements (Skinner, 1957); on self improvement by accepting and assuming causes-effects such as studying and following the corresponding effects, such as overcoming difficulties and learning (Benesh & Weiner, 1988). An attempt is made to prevent the appearance of cognitive dissonance (Festinger, 1968) so that students harmoniously appreciate their abilities and efforts with the results obtained.

The objective of this study is to test the effectiveness of a specific Physics teaching method in activating frontal lobe regions.

Example of application. Newtonian laws

1. Music sounds while the students are getting in the lab. They get involved in the class by linking melodies to the lab and the socratic process. It is a special place, a special atmosphere. It is a subconscious process for the brain.
2. We start the session talking about motion and its causes. Easily the students go up to the force, even though they cannot define it. Precise words at this point are not necessary.
3. We try to get a relationship between forces and kinetics (position, velocity, acceleration). First experiment consists of pushing a chair and seeing what happens. They tend to say no force, no motion.
4. Then we see the scene from the film *Mission to Mars* (https://youtu.be/Gaev_Jo6fRs) (00:49:30 to 00:53:30 approx). A man in space is accelerating by using a sort of a rocket, trying to catch a lost device, but he goes too fast and keeps on moving even though he

is not using the rocket anymore. New questions are suggested. Why cannot this man stop? Is there any force applied? What kind of motion can we see in the different parts of the scene? Is there a different motion law out there? (Aristotle principle) ... They find out the inertia principle.

5. The conversation usually grows up under the teacher´s leading in a maieutic dialogue. How the astronauts start moving? And how do they stop their motion? With apparenty no intention, the students go to the relation between force and acceleration, the second principle.
6. Analyzing the role of the gas and motion they go up to the principle of action-reaction. At this point, the scene is linked with other new scenes under the guidance of the teacher.
7. To reinforce what they have discovered, the students watch more scenes, but now they explain what is happening.
8. The students try to solve some classical problems.
9. An example of CSI contextualized problem:

   A man has died hit by a car in a traffic accident. A 20 m braking was found on the ground. The mass of the vehicle is 1000 kg. An analysis of the brakes indicates that the car was applying a force of 19290 N. The speed limit in that road is 90 km/h. The CSI agent arrests the driver for speeding and charges him for the accident. Why?

   (At proper velocity limit, brake force needed is 15625N, the car was moving at 100 km/h).
10. A guided lab session is introduced. By using different forces (masses) the measure velocity and acceleration of an object to prove the principles. They must design the procedure.
11. To test if the students have learnt the principles, they complete a google form in which they check their answers without the pressure of the result of a test, because is not considered for a final assessment. But the test allows the teacher to know how the students are improving. Some clarifications would be needed and students that have already understood the principles can explain them to others.
12. At the very ending, after showing who Newton was and his milestones, we talk about the philosophical implications of the Newtonian laws: determinism. Do you agree with it or not? What about free will?
13. Students can search for new scenes. They can show and explain their findings in class.
14. Students can create their own problems by using a movie scene or inventing fictionalized situations.
15. We go to skate on ice and test the principles already found.

One student must try to push slightly to another student to start a movement. Are both moving? Why? Who has a bigger acceleration? Who is more massive? Why? What is the *inertial mass*? What principles are related to?

What is the role of the ice in relation to friction? What would be happening if we could avoid ice friction completely? Can we stop moving? What principle is it related to?

What happens if the first student tries to push slightly three aligned students? Is it easier or not? Why? What principle is it related to?

Sometimes the structure of the sessions is not the same (scenes + students argumentation + problems + lab), but we always look for reasoning step by step. Sometimes historical context is taken in first place to play as a pioneer of science, traying to put themselves in place of these people. It all depends on the issue the students have to develop and learn.

METHODS

We used Stroop interference test in its adapted Spanish version (Golden, 2005). It is designed to measure the response of the brain when contradictory information is shown. Stroop interference test assesses both student focus and identification abilities.

The test consists of three sheets. Students are required to read names of colors printed in black ink on the first sheet and name different color patches on the second one. On the third sheet, color-words are printed in an inconsistent color ink (for instance the word "red" is printed in green ink) and the student must say the ink color, not the written word. The student is asked to read as fast as possible all sheets, using 45 seconds in each task.

Scoring formulas:

P: number of words read in the first sheet.

C: number of words read in the second sheet.

PC: number of words read in the third sheet.

PC′: estimated interference.

$$PC' = \frac{C \cdot P}{C+P} \quad (1)$$

The *interference* (inhibition) is (PC-PC′):

$$PC - PC' = PC - \frac{C \cdot P}{C+P} \quad (2)$$

The higher score, the better control of impulsiveness. There is no difference in the results by sex in this test, but there are differences by age. Tabulated correction factors are applied to the scores, according to age and following the instructions of the test version.

Descriptive statistics were utilized for data analysis. Kurtosis-Symmetry and Shapiro-Wilk normality tests were used to evaluate the Gaussian distributions of continuous variables. Comparisons of the two groups were performed with parametric independent samples T-test for continuous variables. All p-values were 2-sided, and p-values below 0.05 were considered significant. All analyses were performed using IBM SPSS 25.0 (SPSS, Inc., Chicago, IL, USA) and Stata 16.

The contradictory information in Physics is shown when we find differences between our misconceptions and the real explanations. The Stroop test is frequently used to study executive functions located in the frontal lobe and these are required to inhibit some reactions or incorrect responses. The anterior cingulate is activated prior to decision making by frontal lobe (Pardo *et al.,* 1990), as it it occurs in learning Physics.

Adults and adolescents activate the same areas of the brain while doing the Stroop test. The only difference is the volume of neurons working on the process (Andrews-Hanna *et al.,* 2011).

We want to know if there is any relationship between a specific way of learning Physics and the executive functions of the brain. Even more, we want to know if these executive functions can be improved by using this brain-based methodology.

The method for this research has been approved by Funcadión Internacional de Educación (FIE), Sociology Department, Pablo de Olavide University and Institute of Biomedical Research of Salamanca.

Participants

Middle class students from high school attending Physics classes at pre-university levels (age range = 15 – 18 years), from Madrid, Spain. All participants gave signed informed consent.

36 male and 33 female students (47,8%) were chosen for this study. Even though the original sample was made up of 112 students, only N=69 fulfill all criteria requirements.

Two groups are contrasted, control and intervention groups. In intervention group the methodology already described is applied. The control group, students from different high schools, was learning in a classic masterclass style.

The results of the Stroop test from both samples are compared.

Various criteria have been used to choose the statistical population, always seeking the sample to be as homogeneous as possible. Exhaustive criteria are taken in order to avoid masked variables.

Inclusion criteria are:

1. Students must be in their corresponding course, according to their age.
2. We want to study the effect of this specific way of teaching. It means the exposition to the method must be as much as possible. Therefore, students from the intervention group must have completed the previous courses with this precise methodology, from the age of 15, onwards.

Exclusion criteria are:

1. Students must not be foreigners, must not have spent two or more years living abroad or have established social routines belonging to other cultures.
2. Students must not suffer from any neurological pathologies (such as AD / ADHD, dyslexia, aphasias, tumors ...) or any other unfavorable physical circumstance (blindness, deafness ...)
3. Students must not have special educational needs.

In addition to the cases already described students who have taken the Stroop test with systematic errors are eliminated from the intervention sample (the number of responses was not reduced in any of the slides as the test progressed).

Control group is chosen from two different high schools.

According to Shapiro-Wilk and Kurtosis-Symmetry tests, every sample in this research has a Gaussian distribution by gender and course, by complete course and by total population. Same number of males and females in control and intervention samples. Thus, the control sample presents an appropriate asymmetry (0,23) and kurtosis (0,59). Students fulfilled common criteria.

Written informed consent was obtained from all participants and parents prior to testing.

Data Availability

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

RESULTS

The inclusion and exclusion criteria imply similar control and intervention samples, as shown in Table 1. In a specific course we find students with different ages, depending on their month of birth.

Table 1.
Characteristics of the sample groups by sex and age. We can see the number of participants in each course with two different methodologies: A Brain-Based Teaching Approach (BBTA method) and master class (classic method).

		BBTA method			**Classic method**		
	Age	Male	Female	Total	Male	Female	Total
Course 1	15-16	19 (61%)	12 (39%)	31 (100%)	19 (61%)	12 (39%)	31 (100%)
Course 2	16-17	9 (43%)	12 (57%)	21 (100%)	17 (45%)	21 (55%)	38 (100%)
Course 3	17-18	8 (47%)	9 (53%)	17 (100%)			
Total		36 (52%)	33 (48%)	69 (100%)	36 (52%)	33 (48%)	69 (100%)

The control sample was completed with 16-17 years old students thanks to the application of tabulated correction factors to the scores, according to age. Kurtosis and asymmetry values are acceptable for Gaussian distributions, as it is shown in Table 2.

Table 2.
Kurtosis-Symmetry (K-S) and Shapiro-Wilk (S-W) normality tests (p-values) of the samples by course.

		BBTA method		**Classic method**	
	Age	K-S	S-W	K-S	S-W
Course 1	15-16	0.403	0.494	0.601	0.586
Course 2	16-17	0.121	0.423	0.660	0.551
Course 3	17-18	0.140	0.684	0.616	0.531
	Total	0.373	0.462	0.415	0.282

In spite of the N of the experiment, both samples fulfill Gaussian criteria. The T-tests and effect sizes of the interventions are shown in Table 3.

Table 3.
Direct scores and T-tests by gender between intervention (BBTA method) and control group (classic method).

	Interference (BBTA method)	**Interference (Classic method)**	**T test p-value**	**Effect size (Cohen's d)**
	Mean (SD)	Mean (SD)		
Male	8.86 (8.75)	5.54 (7.22)	0.084	0.413
Female	7.25 (7.15)	5.47 (4.95)	0.243	0.290
Total	8.09 (8.0)	5.51 (6.20)	0.036	0.361

The perceptible difference in the mean scores is statistically significant ($p < 0.05$) between both complete groups.

DISCUSSION

As these results suggest, it could be inferred that students from the intervention group have a greater capacity to withstand the interference of the test. It means a greater degree of inhibition. These students filter information in a better way and it implies less impulsiveness. It is a greater control by executive functions.

This appreciable difference in the means is statistically significant ($p = 0.036$).

This result is consistent with brain-based teaching approaches, which have already been indicated to be more effective than conventional learning methods in significantly apprehending knowledge of Physics laws (Saleh, 2012). It is proposed that the physiological substrate analyzed in this study may contribute to the explanation of what happens. Not only is the understanding of Newtonian Physics improved, but also the way of judging, of reasoning, due to the necessity of inhibition of impulses or intuitive first ideas about something.

Regarding gender parity, there is a distribution by gender similar to the means offered by the SRPS (Spanish Royal Physics Society) study on the State of Physics in Spain (SRPS, 2018), 55% males and 45% females approximately.

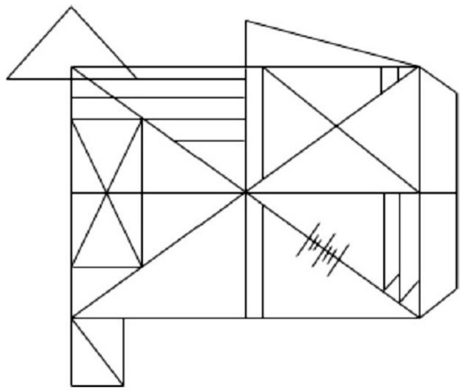
The difference between males and females is not statistically significant, as it would be expected (Dew *et al.,* 2021).

A tipical reason for a difference gender performance use to be the fact that females somehow perceive that they are numerically inferior to males (Maries *et al.,* 2018).

A parity was necessary to overcome the possible inferiority complexes in science or prejudice that females may have concerning themselves, predisposing females to underrate their own capabilities (Wulff *et al.,* 2018). As a result, there is no difference in males and females performance.

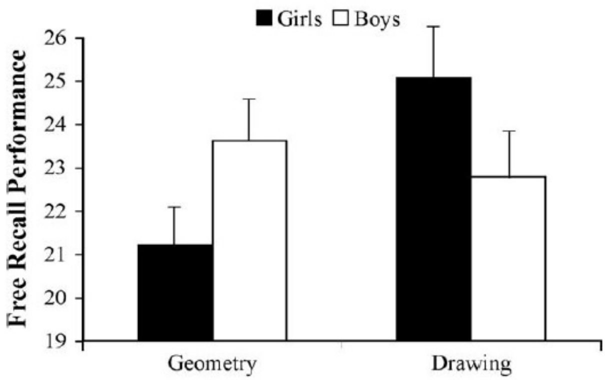
These results are not consistent with the study carried out in France with adolescents who were asked to reproduce a drawing by recalling a picture already seen (Huguet & Régner, 2009). Part of the sample was told to be an exercise in geometry and the other part was told to be an exercise in arts:

Fig. 1.
Image to be reproduced (Huguet et al., 2009).



The results indicated that female students presented better scores when they were told it was an art task. Male students maintained similar values in both approaches:

Fig. 2.
Different results in drawing task (Huguet et al., 2009).



As it is shown, the environment of the test did not condition the female results. The tests in this study were performed during the Physics classes, so there would be a possibility of unconsciousness that associates them with the content of the subject. This effect did not appear.

The environment of freedom and confidence would be the explanation of these positive results.

CONCLUSIONS

The results of this research suggest that there is an increase of the inhibition related to the way of learning. To learn Physics in the proposed way seems to reinforce the executive functions, as far as the Stroop test indicates a statistical significance ($p<0.036$), taking in to account the total group of students compared to the control sample.

Despite the limitations of this study, it seems to be appropriately focused and indicates an effective way of teaching and learning Physics, furthermore is consistent with previous published experiences.

This methodology would be an effective tool for women to overcome their possible complexes in science, as the results shows there is no difference in male and female performance.

The actual scope and the potential of this method as a teaching-learning effective tool is linked with the improvement of executive functions. The students not only learn Physics, but also learn to think in a different environment as the methodology is related to every single level of Bloom´s taxonomy.

Since inhibition processes are important as a previous step to carry out the judgement function, the proposed teaching-learning methodology suggests an improvement of logical reasoning in students.

Relational reasoning is highly recommended in the study of Science, Maths and Engineering (Alexander, 2019), as a powerful tool to improve students' learning and performance. The brain makes a first impression of Nature. Learning is making and rebuilding mental maps and relationships among different inputs. The same difficulty in learning Physics appears in other sciences that imply going further than first impressions and misconceptions. Different science subjects would benefit from this methodology (Mathematics, Chemistry, Geology, Biology...), probably by making some slight adaptations.

As executive functions control impulsivity, the present study would indicate that the applied methodology would be a useful tool for improving self-control and as a critical thinking training.

Conflict of interest

The authors declare that they had no conflicts of interests with respect to their authorship or the publication of this article.

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