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A Revisited Conceptual Change in Mathematical-Physics Education from a Neurodidactic Approach: A Pendulum Inquiry

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Abstract: Learning physics today contains a strong algebraic component, which does not contribute to making an effective conceptual change due to several misunderstandings and misconceptions that students have. Inquiry-based science education methodology (IBSE) is a solution, as well as model-based inquiry (MBI), but no agreement exists regarding which one is the best option. The contribution of both new neuroscientific and cognitive psychology advances is necessary. All these components can be arranged within a transdisciplinary discipline called Neurodidactics. This work presents a neurodidactic proposal to achieve an effective conceptual change. The study involves 171 undergraduate university students and is based on an experimental design (control and experimental groups) with pre- and post-test questionnaires. Results will show the importance of experimentation in mathematical-physics sessions, as well as the importance of visuospatial abilities and the inquiry component offered by the different resources used (virtual simulations and multimedia) in order to obtain a model. In addition, the role of transdisciplinary orientation and the importance of conceptual modeling was tested, obtaining an essential contribution to balance the normally non-significant algebraic approach of physics science, offering altogether a possible new path for scientific learning.

Keywords: neuroscience; conceptual change; transdisciplinarity; inquiry-based science education; model-based inquiry; neurodidactics; conceptual mathematics

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1. Introduction

Teaching physics science requires a change in all educational stages. Fundamentally, teaching is based on memorizing scientific concepts and on solving algebraic problems, as well as on activities for collecting information or questions about reading, relegating hands-on activities to a second place [1]. With respect to algebraic problem solving (the resource mainly used), according to the Bhaskara and Panacharoensawad study, students barely remember or understand how to determine the physical laws and equations involved in the problem [2] because it is like learning a foreign language with symbols but without any context, and mathematics is more than just an empty logical science [3]. Problem-solving methodology by using only mathematical processing leaves too many conceptual gaps [4–6], even though real-life problems are used, because there are some deficiencies in the conceptual knowledge of mathematical analysis, so scientific concepts are not fully consolidated. Consequently, other methodologies are currently being explored. We can find two recent methodologies in science education: (1) *Inquiry-Based Science Education (IBSE)*, which uses *hands-on activities* and constitutes an experimental approach based on asking questions. It does not always begin with a standard "scientific" question, but with students' curiosity [7]. It is more appropriate to refer to inquiry and non-research, where skills and the more conceptual development of science are enhanced [8], promoting conceptual change [9]; and (2) *Model Based Inquiry* (*MBI*). This methodology is characterized by using *minds-on activities*, a construction of knowledge from a model. According to Martínez-Chico et al. [10] and others [11], MBI constitutes a dynamic process based on building simple representations that can describe and predict scientific phenomena, in contrast to IBSE, where a very superficial construction is made [12]. These models can be both conceptual and physical representations (objects, symbols, designs...) that simplify a phenomenon in order to understand its characteristics. To do so, students will have to reconsider their conceptions of scientific events, just like in the IBSE methodology, but with the difference that they will have to design experiments that prove their models [13,14]. Up to now, no consensus exists on which one is more effective for conceptual change, and the role of mathematics in that conceptual change is not clear. We need more educational resources to solve this problem: a neurodidactic approach, one of the objectives of this research.

1.1. Neurodidactics: A Neuroscientific and Psychological Approach to Science Education

Neuroscience is a natural science that investigates how the brain works and how the different parts are connected [15]. Thanks to neuroscientists like Goswami and Howard Jones during the period 2006–2009, a bridge between neuroscience and education began to be established [16]. Neuroscience reveals that the brain's ability to learn depends on the number of neurons and the richness of the connectivity between them. Therefore, if learning is linked to a previous experience, such as daily situations, positive emotions, and motivation, as well as enhanced interdisciplinary concepts, memory and learning are promoted by expanding the formation of neural networks [17–19].

A first current trend was *Brain-Based Learning*, also called *educational neuroscience or neuroeducation*, a term that was coined by Howard Gardner in 2008 [20], offering a tendency to optimize the function of the human brain through educational practices [21], especially with reading or mathematical skills [22]. Saleh used this methodology to teach Newtonian physics in a conceptual way, obtaining a reasonable improvement. Recent studies by this researcher show similar results, making it possible to reduce the differentiation between genders [23]. The key is to generate a positive climate and an active process for perception, together with the property of brain plasticity, a characteristic of the brain that is being constantly transformed throughout life, adapting to changes in the environment, which can make learning more significant if we offer the most suitable conditions [17,24].

In the final step we can find the *Mind, Brain, and Education science* or *neurodidactics* [25], where the field of psychology is included, obtaining a more accepted final trend for an education based on brain science [26], which can be effective against the different neuromyths [27,28], offering a transdisciplinary working field [29,30]. The *neurodidactics* trend helps educators to face four challenges [31]: (1) recognizing ineffective educational models; (2) replacing those models with others by using cognitive neuroscience orientations; (3) practicing with those models in diverse contexts; and (4) obtaining more effective collaboration in more complex environments.

The methodologies applied in the traditional science classroom do not encourage intense transdisciplinary and meaningful brain activity [23]. As we can see, neurodidactics offers a path of improved educational performance that integrates some aspects of IBSE and MBI (observation, motivation and curiosity, attention, real-life inquiry phenomena, and collaborative learning) offering an enhanced emerging direction for future science education. We will check these contributions through a conceptual change effect measurement.

1.2. Conceptual Change in Science Education: A Revisited Approach from a Neurodidactic Viewpoint

The interest in research in physics education has been increasing since the year 2000 [32]. There are three important topics which are now in the spotlight: "learning strategies", "concept", and "reasoning process". The topic of problem solving has received a lot of attention recently, such as introductory physics and school programs, as well as STEM-TPACK learning [33]. However, conceptual change and misconception are considered a parallel area of interest [32] that need a revisited study using another approach, this being the main objective of our work.

Several studies support the effectiveness of the conceptual approach in science, proposing the necessity of a change in classroom teaching because generally, students provide explanations that do not agree with the vision of science due to misconceptions [34]. These ideas are difficult to eradicate once they have been established [35], so learning something new would be in conflict with what has already been learned. As an aside, the frequency of publications for this field of study is shown in Figure 1. It can be observed that the tendency is a decrease in the number of publications per year from 2010 until now. For that reason, it is necessary to open new guidelines to support this area, as follows. From the various existing theories about what happens to misconceptions when a change is made [36], the Foisy et al. review in 2015 offers the most widely accepted one, resulting in two arguments [37]: (1) ideas are transformed or replaced and do not exist when the change is made; (2) ideas are present, although conceptual change is made, coexisting with the new scientific knowledge.

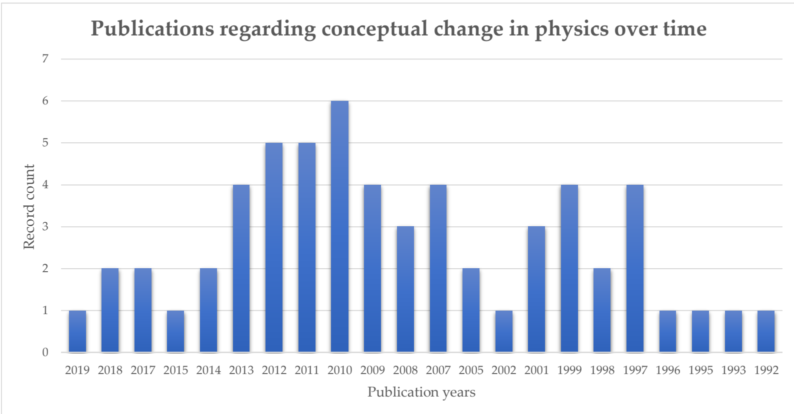

Figure 1. Publications regarding conceptual change in physics over time, using the Web of Science website.

The solution to this divergence has been provided by neuroscience, confirming that these ideas remain in the brain's neural network to be inhibited only by the person who knows the scientific response (adjacent neural network), as demonstrated by Masson et al. with functional magnetic resonance imaging [38]. That means that a broader spectrum of activities is required to overcome this. Recent studies show that inhibition is slower in younger adolescent students than in university students [39]. It is important to emphasize that only teachers who are conscious of the students' misconceptions can successfully achieve effective conceptual changes [40]. Conceptual change is made by the working memory, an executive function ability, especially in problem solving [41], where verbal and visuospatial information (forms, locations and movements) are characterized, being the ones most used for mathematical learning [38,42] and science [43], especially for conceptual learning. According to Rhodes et al. it is confirmed that the working memory is predictive with respect to the conceptual understanding of chemistry or biology [44], where students have to apply the acquired scientific knowledge to carry out a conceptual change [45]. Using multiple visual representations, it can be possible to cope with abstract mathematical problems (IBSE contribution), being helpful for understanding and applying physical concepts [43], resulting in a possible modeling of the problem, as well as activating perception [46]. A recent neuroscientific review of the conceptual change in science learning says that the neural process is complex, so a neuroscientific model is not yet available [47].

Therefore, we must find another field that can offer a predictive conceptual change model to improve science learning: the area of cognitive psychology. Didactics, neuroscience, and now psychology guidelines could work together from a neurodidactic approach that could improve learning. Nadelson et al. in 2018 proposed in their review a psychological dynamic model that involves some neuroscientific aspects of learning, such as emotions and the context of the message, motivation, and the students' existing ideas: the so-called *Dynamic Model of Conceptual Change* (DMCC) [48]. According to the authors, the basic framework for the DMCC is based on four essential stages: (1) the message (observations, experiences, or interactions), (2) learner recognition and consideration of the message (usefulness, plausibility), (3) learner engagement with processing the message in behavioral and affective aspects (emotion and motivation), and (4) acceptance, leading to conceptual change. At present, this method has been postulated by the authors without any application. In this work, we will prove its effectiveness and its possible improvements in conceptual change by the configuration of a *neurodidactic* proposal using a classic example of the physical sciences: the physical pendulum.

1.3. The Physical Pendulum: A Case of Study to Test the Neurodidactic Proposal

The beginning of the use of a pendulum for pedagogical purposes was carried out by Piaget and Inhelder in 1955 to understand thought maturity by means of a logical-mathematical model [49]. The study consists of considering variables independently (*ceteris paribus* principle), such as the length of the pendulum, mass, angle of oscillation, and thrust force [50]. With the pendulum, Piaget classified four different cognitive stages: sensorimotor (0–2 years), pre-operational (2–7 years), concrete operations (7–11 years) and formal operations (11 years and older) [51]. The stage of formal operations is related to the beginning of scientific thought. The pendulum requires the induction of experimental hypotheses, making combinations of variables and the establishment of logical sequences (if "a" is "b", then...) to set a plausible hypothesis. In addition, the movement of the pendulum has been used to find out teachers' misconceptions [52,53], to learn the scientific method [50,54], and to build and understand physics laws of nature for gravity calculation [55,56]. At present, it is being used to introduce technological resources that improve science learning by means of using a mobile phone, thanks to the sensors this device contains [57,58].

Another possibility is to use pendulum virtual simulations to engage and motivate students in scientific experiences. These stand out for their interactivity, observing variables and visualizations that may go unnoticed by the students [59], helping them to understand and learn how to make conceptual changes [60], as well as reducing the cost of experiments and time, creating the opportunity to establish hypotheses and debates [61]. Therefore, using simulations and the practical experimentation with a physical pendulum combined with audio-visual media and conceptual issues, research will be made to determine the effectiveness of these neurodidactic guidelines in order to achieve a conceptual change in university students.

2. Materials and Methods

2.1. Hypothesis

The hypothesis of this work concerns the improvement of effective conceptual change in physics education through the application of neurodidactic principles based on an increase in experimentation (multisensoriality), motivation and resources (virtual and multimedia activities), obtaining a neuroeducational vision for a complete conceptual change, and facing the mathematical-algebraic aspect of physics, as we can conclude from literature in the introduction section. That means reinforcing the didactics of IBSE methodology with respect to MBI in the proposal, to confirm that IBSE methodology is better than MBI to obtain an effective conceptual change.

2.2. Objectives

From the hypothesis, we can obtain two main objectives: (1) the transdisciplinary effect in the learning of scientific concepts (neurodidactic areas contribution) and (2) the influence of the use of the IBSE methodology (sensorial experiences, questions, and visuospatial-virtual simulations resources), with respect to modeling (MBI) and the role of the algebraic-mathematical component in the neurodidactic proposal in order to achieve an effective conceptual change.

2.3. Participants

A study has been carried out with 171 university students from *La Inmaculada teaching center (LITC)* at the University of Granada, Spain (3rd year undergraduate students of the bachelor's degree in primary education). They were divided into two groups: (1) the *control group*: 74 students, aged 20–22 years (M = 21.6, SD = 0.59) and (2) the *experimental group*: 97 students, aged 20–22 years (M = 21.9, SD = 0.56), all of them with basic concepts of high school physics.

2.4. Instrument: Validation and Reliability

An ad hoc pre- and post-test was conducted with the same seven questions, which can be seen in Table 1. The questionnaire was first validated by the expert judgement and triangulation procedure. Five researchers from different fields (experimental sciences, mathematics, school organization, and cognitive psychology) established the validity of their content, achieving a unanimous agreement.

Table 1. Instrument for testing the neurodidactic sessions (pre-test and post-test).

Items	Questions	Responses
1	What makes a pendulum swing?	(a) air. (b) gravity. (c) thrust force.
2	Is the use of mathematics essential to understand scientific phenomena?	(a) no, mathematics is theoretical, and science explains natural phenomena. (b) yes, science needs mathematics to explain the world around us. (c) no, science does not need abstract expressions to describe natural phenomena.
3	In your experience, when should scientific concepts be explained?	(a) sensorimotor stage. (b) pre-operational stage. (c) concrete operational stage. (d) formal operational stage.
4	What variables affect the movement of a pendulum? Mark your choices with a cross.	(a) mass of the oscillating object. (b) length of the string. (c) amplitude. (d) thrust force.
5	When you change the angle of oscillation, you observe that:	(a) it takes more space and thus more time as the angle increases. (b) it takes less time as the angle increases due to higher acceleration of the mass. (c) it takes the same time because a greater angle causes a greater velocity of oscillation. (d) None of the above.
6	A female NASA astronaut, at a certain moment, takes out the pendant that her boyfriend gave her to remember him by. What will happen to the pendant when she drops it?	(a) oscillate faster than on the Earth. (b) oscillate the same as on the Earth. (c) oscillate more slowly than on the Earth because there is less gravity. (d) oscillate more slowly than on the Earth because there is no gravity on the Moon. (e) not oscillate on the Moon because there is no air. (f) not oscillate on the Moon because there is no gravity.
7	How many of these aspects do you think are present in learning physics?	(a) psychological. (b) social. (c) mathematical. (d) chemical. (e) pedagogical. (f) physical. (g) geometrical. (h) cognitive development theory. (i) cultural.

In addition, a factor validation for the instrument was carried out. The Kaiser–Meyer–Olkin (KMO) factor adequacy, which correlates pairs of variables when a value of 0.6 or higher is obtained [62], generates a 0.67 value, and the Barlett sphericity test reaches 272.4927 (p-value < 0.001) in the instrument. These data deemed that the answers are substantially related, justifying the realization of factor analysis. We obtained three factors using Kaiser–Guttman criteria [63] and using the Rotation Method that consists of the Varimax method with Kaiser normalization [64,65], explaining 50.4% of the variance (see Table 2).

Table 2. Variance explained according to factors and Kaiser–Guttman criteria.

	Factor 1	Factor 2	Factor 3
% Variance	28.1	13.4	8.9
% Accumulated	28.1	41.5	50.4
Kaiser–Guttman criteria (eigenvalues > 1)	2.79	1.13	1.03

Each factor corresponds to a category that consists of groups with different items of the instrument, items that were ordered according to the degree of saturation by the Varimax statistical method (see Table 3), obtaining: (1) Factor 1 or Neurodidactics of Science category. This factor group refers to items such as 4, 5, and 7 in the questionnaire of Table 1 and consists of the different science methodologies used when adopting a transdisciplinary area approach; (2) Factor 2 or Cognitive Psychology refers to items 1 and 3 and is related to the cognitive aspects of physics; and (3) Factor 3 or Neuroeducational category refers to items 2 and 6, related to motivation, resources, neuroscience, and the role of mathematics.

Table 3. Matrix-rotated component and Cronbach's Alpha coefficients.

Items	Factor 1 Neurodidactics of Science	Factor 2 Cognitive Psychology	Factor 3 Neuroeducation	Cronbach's Alpha If the Item is Removed
1		0.142		0.72
2			0.391	0.71
3		0.597		0.69
4	0.828			0.55
5	0.728			0.64
6			0.644	0.74
7	0.845			0.55
Total Cronbach's alpha				0.71

Reliability was ensured by internal consistency using Cronbach's alpha parameter for the control and experimental groups (university students). We obtained different values for the pre-test: $\alpha_{\text{Cronbach-Control group}} = 0.51$; $\alpha_{\text{Cronbach-Experimental group}} = 0.71$; the value α for the pre-test shows an acceptable reliability for the experimental group [66]. A study of Cronbach's alpha when a selected item is removed is included in Table 3. In fact, a similarity of responses has been obtained for the instrument, where each item leads to obtaining the common objective: achieving a conceptual change.

Additionally, to check the effectiveness of the intervention, the post-test Cronbach's alpha generated the following values: $\alpha_{\text{Cronbach-Control group}} = 0.44$; $\alpha_{\text{Cronbach Experimental group}} = 0.37$, showing that a conceptual change, in a first instance, could be occurring in the experimental group because the answers did not reveal the substantial variations that were shown in the pre-test [67].

2.5. Statistic Design

An experimental pre- and post-test design including the control and experimental groups was carried out. For the proposal evaluation, a t-comparison test of related and unrelated samples (control–control, experimental–experimental, and control–experimental groups) were applied together with Cohen's effect size in order to observe changes when the practical sessions were carried out. To do that, mean values of scores were calculated [66], as well as Hake's N-gain [4], to observe the learning effect, as well as the possible linear regression and the different correlations of the different items of the questionnaire.

Each item was studied independently to observe changes in students after practical sessions in both groups. To quantify the effect, we selected two statistical studies of comparison (inferential studies) due to the type of questions used: (1) for multiple-response items (questions 4 and 7), a Chi-squared (χ^2) independence test (frequency treatment) for nominal data was carried out to compare the non-symmetric response count before and after the sessions (students could select all the responses of the item), checked by the exact Fisher test for two tails; (2) for single-choice questions (items 1, 2, 3, 5 and 6), a paired sample test of McNemar (2 × 2), McNemar-Bowker ($n \times n$), the Monte Carlo method, or the Fisher exact test were used, as appropriate, as literature suggests for before and after design tests [66].

Gender differentiation will not be considered in this paper. The data were processed with R free software (v.3.6.1), under RStudio programming (v.1.3.959) through the installation of several specialized statistical packages.

2.6. Procedure

The proposal involved a pendulum experimental study (univariate scientific method) for both groups' sessions (control and experimental), where students studied different variables: mass, angle or amplitude, the length of the rope, and the thrust force, emphasizing the importance of reducing errors in measurement, choosing ten oscillations over time in order to smooth out random errors in measurement [68], where the role of mathematics in physics and the possible conceptualization and modeling was taken into account.

However, only in the experimental group were transdisciplinary components included, such as: (1) Piaget's cognitive development theory and its implications in education, as well as its veracity in terms of new neuroscientific advances [69]; (2) neuroeducative and psychological aspects (DMCC method). Furthermore, different resources as well as a virtual pendulum simulator, videos, interactive dialogues, and questions were included, observing the changes and successes of these incorporations in order to obtain a conceptual change.

3. Results

3.1. Individual Results for Each Item of the Questionnaire

To evaluate if the control and experimental groups were similar at the beginning of the research (pre-test), a statistical t test study for unrelated samples was carried out. The results of the items of the questionnaire were transformed into a 10-point scale, finding $t = 1.6062$, df = 11.671, p-value = 0.1349, d = 0.858 (large effect size), and Cohen's effect being "d". This result ensures group homogeneity for future comparisons, increasing the reliability of this research.

The individual results of the pre- and post-tests are presented for both groups as follows. With respect to the first item (see Table 1), we asked what makes a pendulum swing, giving three possible answers: (a) air; (b) gravity; or (c) thrust force. As a single-choice response item, a test comparison study of paired samples was carried out based on the McNemar–Bowker test (3 × 3), obtaining: (1) the control group: $\chi^2_{\text{McNemar}} = 17.66$, df = 3, p-value < 0.001, Cramer's V value = 0.15; and (2) the experimental group: $\chi^2_{\text{McNemar}} = 4.0$, p-value = 0.262, Cramer's V value = 0.13. In the case of the control group, there was a significant increase in the choice of gravity as an operating factor—option (b)—from 56.8% to 86.5% (a moderate increase as Cramer's V value indicates). However, in the experimental group, no significant differences were observed, just an increase of 9.28% after practical sessions for option (b) (gravity) from 63.92% to 73.2%.

The second item concerns the relationship between mathematics and science (see Table 1). In both groups, options (b) and (c) were hardly chosen by the students, as opposed to option (a). The results did not show significant differences between the two groups: (1) the control group: $\chi^2_{\text{McNemar}} = 2.0435$, df = 1, p-value = 0.563, Cramer's V = 0.27; and (2) the experimental group: $\chi^2_{\text{McNemar}} = 1.4545$, df = 1, p-value = 0.228, Cramer's V = 0.05. In the control group, students equally selected options (b) and (c) in both tests, but in the experimental group, almost 92.0% of students considered that mathematics was necessary to explain scientific phenomena (answer (b)).

Item 3 deals with aspects of Jean Piaget's cognitive development theory (Figure 2). Results did not show significant differences in the control group using the McNemar–Bowker test ($\chi^2_{\text{McNemar}} = 5.1429$, df = 3, p-value = 0.161, Cramer's V = 0.319). The concrete operational stage—answer (c)—was the most selected answer both before (64.8%) and after (74.8%) the sessions. With respect to the experimental group, the McNemar–Bowker test did not obtain a reliable result due to inconsistencies in the analysis, so a similar analysis of paired samples was carried out using a Fisher exact test where no significant results were obtained (p-value = 0.591). In order to observe differences, the symmetry of the Monte Carlo method generated only a significant result between (c) to (d) answer comparison (Events = $6.68 \cdot 10^{12}$, p-value < 0.001, Cramer's V value = 0.24). A substantial increase in the formal operations stage was obtained (from 27.8% to 64.9%) as opposed to a decrease in the concrete operations stage (from 50.5% to 25.8%), delaying physics teaching to the formal operations stage because of the need for abstract thought, as Piaget concluded [49].

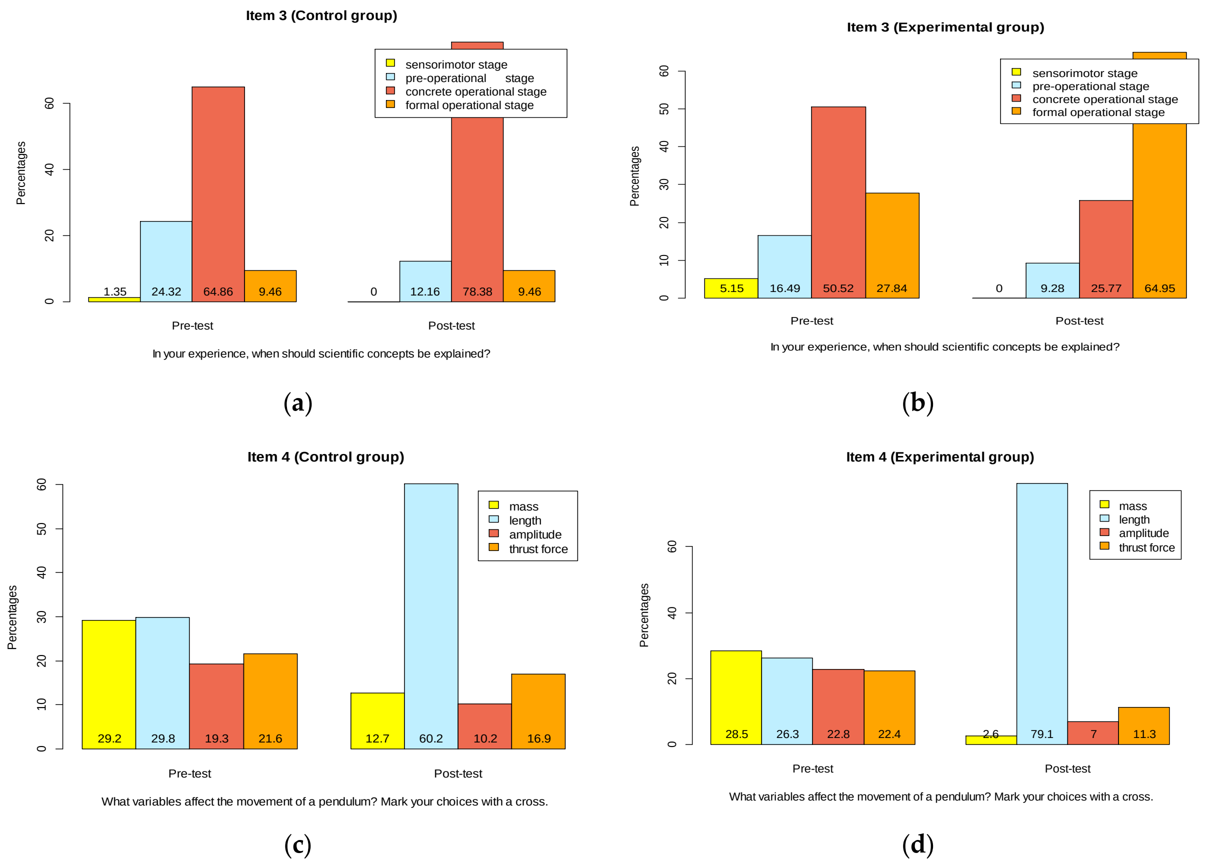

Figure 2. Item 3 is based on cognitive-algebraic thinking: (**a**) in the control group, it is not observed a relevant change; (**b**) in the experimental group, a significative change is observed, reinforcing the formal operations stage because of the need for abstract thought. In item 4, the length of pendulum choice was the main parameter selected in both groups, (**c**) and (**d**), thanks to an experimental interaction (inquiry method), being more efficient in experimental group (**d**).

Item 4 refers to variables that affect the movement of the pendulum (see Figure 2). This was a question where several options could be selected simultaneously, obtaining a non-symmetrical matrix of results. In this case, a Chi-squared (χ^2) independence test was carried out, obtaining significant results. For the control group, a moderate significance was obtained (χ^2 = 28.224, df = 3, p-value < 0.001, Cramer's V value = 0.313). However, for the experimental group, a large effect size was obtained, as Cramer's V value indicates (χ^2 = 90.295, df = 3, p-value < 0.001, Cramer's V value = 0.51). In both groups, students made an equally balanced choice of responses before the sessions. However, after the experimental sessions, only two answers were mostly selected: the length of the pendulum, obtaining an increment of 30.4% for the control group and 52.8% for the experimental group, and the thrust force, obtaining a decrease of 4.7% for the control group and 11.1% for the experimental group. Amplitude (c) and thrust force (d) were associated variables in both groups (p-value > 0.05). In general, the best results were obtained by the experimental group in this item.

The fifth item corresponds to a specific question in conceptual physics (angle oscillation). The control group obtained significant results only by the Monte Carlo method (Events = $3.09{\cdot}10^{14}$, p-value < 0.001, Cramer's V value = 0.59). A change from the predominant pre-test answer (a) (48.6%) with respect to the post-test correct answer (c) (83.8%) was observed, although the students did not question why this phenomenon occurred. The Monte Carlo method was also used with the experimental group, due to similar McNemar–Bowker test inconsistencies shown in the control group, obtaining significant results with a large effect size (Events = $3.09{\cdot}10^{14}$, p-value < 0.001, Cramer's V value = 0.59). In this case, it is interesting to note that the choice of the correct answer (c) was made in almost the same proportion before (54.6%) and after (46.4%) the sessions, whereas for the answer (d): "None of the above", a remarkable increase of 41.2% was observed, obtaining 53.6%, which makes us questions why the correct answer (c) was not chosen by the students. The failure to choose answers (a) and (b) after the practical sessions is considered as moderate progress.

Item 6 corresponds to pendulum movement on the Moon. For the control group, no results were obtained using the McNemar–Bowker and Monte Carlo tests because of inconsistences; only Fisher's exact test could be considered (p-value = 0.1625, Cramer's V value = 0.298), obtaining a non-significant result, where the percentage of responses of the right answer (c), lower oscillation on the Moon because there is less gravity (from 33.8% to 52.7%), did not result in a complete conceptual change. Regarding the experimental group, the Monte Carlo and Fisher exact tests generated significant results with a large effect size (Events = $6.76{\cdot}10^{22}$, p-value < 0.001, Fisher exact test, p-value < 0.001, Cramer's V value = 0.60). The response (c) had an increase (from 59.8% to 77.3%), as well as the response (f) (22.7%), with the elimination of the no air option (see Figure 3). Option (c) was reinforced, thus achieving a complete conceptual change. This change was possible in this group thanks to the use of different resources, such as: (1) videos of the pendulum oscillation on the Moon (Apollo 14 mission) and movement of objects in zero gravity; and (2) virtual simulation of the PhET portal of the University of Colorado entitled *Pendulum Lab* (*https://phet.colorado.edu/en/simulation/pendulum-lab*, 15 December 2020). However, some students had still not learned the fact that gravity exists on the Moon (22.7%).

The last multiple-choice question concerns interdisciplinary areas used in the proposal. For the control group, no resources were used. The complete independence test (several options could be selected simultaneously) showed a non-significant result (χ^2 = 9.943, df = 8, p-value = 0.269, Fisher's test, p-value = 0.264, Cramer's V value = 0.132), in which mathematical, physical, and geometric options were the most frequently selected answers (Figure 3). Conversely, the results of the complete independence test for the experimental group were significant: χ^2 = 79.0716, df = 8, p-value < 0.001, Fisher's test, p-value < 0.001, Cramer's V value = 0.31. To understand this result more clearly, we tried grouping areas, observing the existence of two main groups: (1) *social science group*: we observe similarities of change when psychological, social, pedagogical, cognitive development, and cultural areas were grouped together (χ^2 = 4. 7655, df = 4, p-value = 0.312, Fisher's test, p-value = 0.312, Cramer's V value = 0.14); and (2) *STEM (science, technology, engineering and mathematics) type group*: when mathematical, chemical, physical, and geometrical aspects were grouped together. Only minor changes were observed in this last group (χ^2 = 0.4384, df = 3, p-value = 0.932, Fisher's test, p-value = 0.932, Cramer's V value = 0.03). Results showed a significant increase of 49.2% in the first area (social sciences) with respect to STEM-type content, improving the transdisciplinary social science component of learning (a neurodidactic component), moderately achieving the first objective. A summary with the results and observations of all the statistical studies can be found in Table 4.

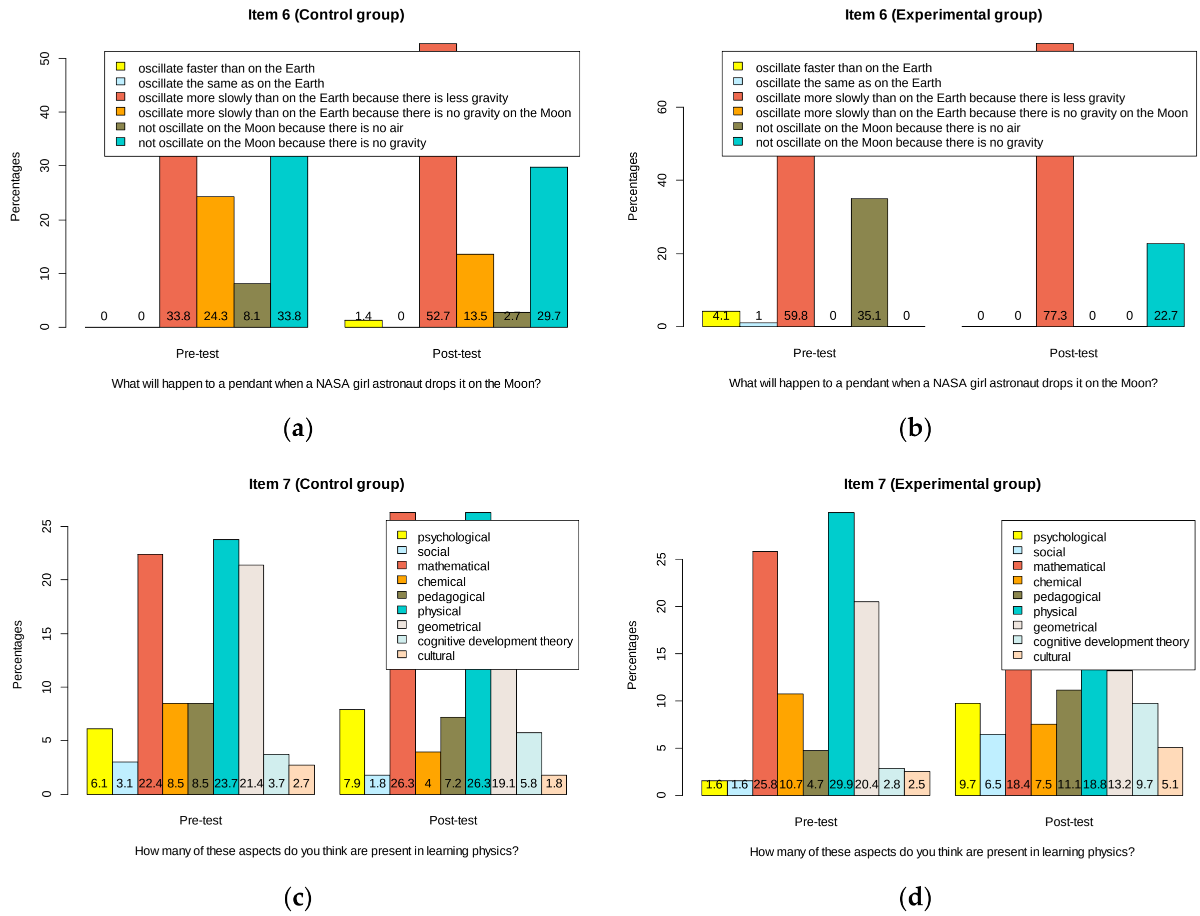

Figure 3. In the item 6, (**a**) the control group maintained statistically the same responses, but in experimental group (**b**), a conceptual change was observed. Gravity was the reason why a pendulum swings. In the item 7, the control group (**c**) nearly noticed differences in the different areas, but in experimental group (**d**), the psychological, pedagogical, social, cognitive development, and cultural aspects (social science group) obtained an increase by using several resources.

Table 4. Summary of the inferential data obtained through the pre- and post-tests, as well as the observed changes obtained by the experimental group.

Item	Experimental Group Inferential Results		
	$\chi^2/\chi^2_{McNemar}$/Monte Carlo	p-Value [1]/Cramer's V	Observations
1	4.0	0.262/0.13	No change: gravity moves the pendulum on Earth.
2	1.454	0.228/0.05	No change: science needs mathematics.
3	$6.68 \cdot 10^{12}$	Whole item: 0.591/0.24 Answers (c) and (d) <0.001	Moderate change to formal operations: abstract thought is needed to understand physical phenomena.
4	90.295	<0.001/0.51	Significant change in pendulum variables: experimentation inquiry is needed to discover the laws of nature.
5	$3.09 \cdot 10^{14}$	<0.001/0.59	Substantial change in reasoning (conceptualization). Modeling is needed. Algebraic component does not help conceptual thinking.
6	$6.76 \cdot 10^{22}$	<0.001/0.60	Significant change due to the use of several resources (videos and simulations) and motivation, increasing conceptual thinking in physics.
7	79.072	<0.001/0.31	Moderate increase in transdisciplinarity.

[1] Significance by Bonferroni criteria: p-value < 0.05/nº of items. Then, p-value < 0.007.

3.2. Overall Neurodidactic Proposal Results

For a quantitative effect of the overall proposal, scores were calculated for each item on a 10-point scale, as shown in Table 5. To determine the significance of the pedagogical performance, a t test for before and after the questionnaire sessions was carried out for related samples with Cohen's effect "d" size for both groups, finding: (1) the control group: t = 2.3233, df = 6, p-value = 0.059, d = 1.01, a non-significant result; (2) the experimental group: t = 3.3554, df = 6, p-value = 0.015, d = 0.98, a value that indicates a significant difference (significance: $p\text{-value} < 0.05$) with a large effect size, obtaining in this group an improvement in the physics teaching–learning process. Due to the fact that normalized distributions of the data were obtained (Shapiro–Wilks test of normality for small samples: pre-test: (1) the control group: W = 0.9214, p-value = 0.480 and (2) the experimental group: W = 0.9346, p-value = 0.591; post-test: (1) the control group: W = 0.949, p-value = 0.726 and (2) the experimental group W = 0.9339, p-value = 0.584), it was not necessary to perform non-parametric inference comparison tests.

Table 5. Categorization, score (over 10 points), and gains obtained from the different items of the pre- and post-test questionnaires for both groups. Only significant linear regression was obtained for the experimental group.

Item	**Control Group Results**			
	Pre-Test	**Post-Test**	**<g>**	**Gain**
1	5.68	8.65	0.69	High
2	4.32	4.32	0.00	Low
3	7.06	7.03	−0.01	Low
4	7.03	9.73	0.91	High
5	2.57	8.38	0.78	High
6	3.38	5.27	0.29	Medium
7	5.69	5.66	−0.01	Low
Total	5.1 ± 1.7	7.0 ± 2.0	0.39	Medium
Item	**Experimental Group Results**			
	Pre-test	**Post-test**	**<g>**	**Gain**
1	6.39	7.32	0.26	Low
2	9.18	9.69	0.62	Medium
3	7.53	8.89	0.55	Medium
4	6.19	9.38	0.84	High
5	5.46	5.36	-0.02	Low
6	5.98	7.73	0.44	Medium
7	4.69	7.26	0.42	Medium
Total	6.5±1.5	7.9±1.5	0.48	Medium
Lineal Regression in the Experimental Group				
Coefficients	Estimate	Std. Error	t value	p-value
Intercept	4.1922	0.894	4.688	0.018
Pre-test	0.5901	0.129	4.568	0.019
Residual standard error		0.437		
Adjusted R-squared	0.8324			
F-statistic	20.87			0.020

The effectiveness of each item and the overall proposal can also be quantified through the standardized gain (<g>) designed by Richard Hake for pre- and post-test questionnaires shown in Table 5 [4,70,71]:

$$\langle g \rangle = \frac{\%\ \text{actual gain}}{\%\ \text{potential gain}} = \frac{\%\ \text{posttest score} - \%\ \text{pretest score}}{100 - \%\ \text{pretest score}} \quad (1)$$

Hake's (1998) criteria for <g> (Equation (1)) is: (1) learning outcomes with a "high gain" if <g> $\geq$ 0.7; (2) learning outcomes with a "medium gain" if 0.7 < <g> $\leq$ 0.3; and (3) learning outcomes with a "low gain" if <g> < 0.3. We cannot consider Hake's criteria for each item for the control group because non-significant global *t* test results support that. However, gains for significant *t* test results (the experimental group) can be considered, showing that the greatest contribution corresponds to item 4, increasing the factor 1 (Neurodidactics of Science category). In fact, we can infer that the procedure lacks the advantages of model-based learning (item 5), obtaining a moderate total gain of 0.48, which shows the importance of including actions that encourage modeling in order to achieve a complete conceptual change, which will be discussed later.

To further clarify the effect and prediction of the neurodidactic proposal, a linear regression was performed using Table 5 values. A linear regression was obtained only with the experimental group. Once items 4 and 5 were eliminated due to their having values outside of the regression confidence intervals and Cook's distances (outliers), the following expression was obtained as well as its goodness of fit: *Posttest = 4.19 + 0.59·Pretest*; R^2 = 0.83, F = 20.87, *p*-value = 0.02, obtaining a moderate effectiveness of (59 $\pm$ 13)% (slope), in accordance with Hake's parameter prediction. This implies that the pedagogical intervention for items 4 and 5 must be balanced.

In addition, a correlation study was carried out to check the relationships between the different categories to identify their role in the proposal (Table 6).

Table 6. Correlation matrix (orange color) and statistical *p*-values (blue color) for the control and experimental groups.

Items Correlations [1]	Categories (*p*-Values) [1] (the Control Group)							
	1	**2**	**3**	**4**	**5**	**6**	**7 (Social Sciences)**	**7 (STEM)**
1	1.0/0.0	0.65	0.21	0.57	0.00	0.13	0.53	0.69
2	−0.05	1.0/0.0	0.66	0.21	0.08	0.18	0.28	0.38
3	0.15	0.05	1.0/0.0	0.93	0.65	0.13	0.43	0.95
4	−0.07	0.15	−0.01	1.0/0.0	0.53	0.18	0.38	0.00
5	0.47	−0.21	0.05	−0.07	1.0/0.0	0.84	0.33	0.66
6	0.18	−0.16	0.18	−0.16	0.02	1.0/0.0	0.64	0.34
7 Social Sciences	0.07	−0.13	−0.09	0.10	0.11	0.06	1.0/0.0	0.53
7 STEM	−0.05	0.10	−0.01	0.70	-0.05	−0.11	0.07	1.0/0.0

Items Correlations [1]	Categories (*p*-Values) [1] (the Experimental Group)							
	1	**2**	**3**	**4**	**5**	**6**	**7 (Social Sciences)**	**7 (STEM)**
1	1.0/0.0	0.00	0.23	0.13	0.63	0.96	0.73	0.22
2	0.30	1.0/0.0	0.02	0.66	0.10	0.00	0.04	0.72
3	0.12	0.24	1.0/0.0	0.14	0.53	0.65	0.42	0.55
4	−0.16	−0.05	0.15	1.0/0.0	0.86	0.72	0.74	0.00
5	−0.05	−0.17	0.06	0.02	1.0/0.0	0.29	0.00	0.06
6	0.01	0.33	0.05	−0.04	−0.11	1.0/0.0	0.03	0.27
7 Social Sciences	0.03	0.20	−0.08	0.03	−0.81	0.22	1.0/0.0	0.02
7 STEM	−0.13	−0.04	−0.06	0.59	−0.19	−0.11	0.24	1.0/0.0

[1] Correlations (bright orange color) and *p*-values (blue color) has been colored to show the nature of the results the table provides.

For the control group, there are only two significant correlations: (1) the relationship between items 4 and 5 (r = 0.47, *p*-value < 0.001), selecting a significance of *p*-value < 0.05, suggesting that the concept of gravity could be well established; and (2) item 4 and 7-STEM (r = 0.7, *p*-value < 0.001), where experimentation generates knowledge by involving STEM disciplines. We can conclude that in the control group there has been an improvement in some aspects of physics learning, but a lack of motivational and conceptual learning is still noticeable.

For the experimental group, the greatest correlation values, eliminating those items that were not individually statistically significant (1 and 2), were the relationships: 7-Social sciences: 7-STEM (r = 0.24, p-value = 0.02), 7-Social sciences: item 6 (r = 0.22, p-value = 0.03), the 7-STEM: item 4 relationship (r = 0.59, p-value = 0.0) being the greatest of all. This means that social sciences encourage the STEM approach and the use of different resources, improving learning. However, the social science component did not by itself strengthen the creation of models (item 5), just the opposite, as shown by the negative correlation (r = −0.84, p-value = 0.0).

4. Discussion

Results show that, for both groups, the concept of gravity does not seem to be a well-established term when it is proposed in other contexts. When different videos and virtual simulations were presented in the experimental group, most of the students learned that pendulum oscillation is lower on the Moon and a minority thought that a non-oscillation occurs, because they supposed that there was no gravity on the Moon, demonstrating in all cases that the force of gravity made a pendulum oscillate, obtaining a conceptual change. The reason for this is that an interesting message was received using resources [72], which provided a creative learning environment, giving them plausible answers [73] which they were able to accept emotionally, thus establishing a change and confirming the validity of the DMCC method sequence presented here.

In the case of the mathematics-physics relationship, the control group did not affirm the complete use of symbolic models to explain the real world, an aspect that was confirmed by the experimental group, valuing the importance of mathematics for phenomena prediction.

By performing a univariate experimental study of a pendulum (item 4), experimentation contributed to physics learning in both groups, increasing the algebraic content in the experimental group due to the capacity for abstract thought that a student must have to understand the physical laws, delaying the study of physics in this group to the formal operations stage (Piaget). Furthermore, the conceptual activities and visual resources help to balance algebraic contribution because they make algebraic expressions more understandable, thus increasing conceptual content [74]. It is possible at early ages to understand some abstract ideas, participate in inquiry processes, and make inferences through experimentation thanks to the brain plasticity that neuroscience affirms [75]. This suggests a questioning of the ages proposed by Piaget [76], as students of the experimental group confirmed at the end of the sessions.

The angle–period relationship of the pendulum (conceptual physics question, item 5) generated a contradictory response: the students experimentally understood that the angle did not affect the period of the pendulum, option (c) being the correct answer, as was chosen by all of the control group. However, this answer was not widely chosen by the experimental group, suggesting that the answer was not found in the questionnaire for a significant percentage of students. That means they wanted another more plausible, conceptual, and understandable response, rejecting in the first instance symbolic models as the only explanation. Effectively, answer (c) implies a verbalization of a symbolic model based on predictive pendulum behavior ($t = e/v$). They appreciated the importance of mathematical expressions in physics, but they needed more, a real conceptual reason for gravity itself achieving metacognition, a conceptual model, obtaining a promising attitude.

Finally, the experimental group students identified the introduction of transdisciplinary contents in the proposal. The results showed that this effect did not contribute to a general conceptual change, but it did improve the context and the usefulness of the message as the correlation study revealed [18], activating the students' attention thanks to the brain interconnectivity necessary for conceptual learning [77], which facilitates assimilation, reasoning and acceptance [78].

In conclusion, using the Varimax method (factorial study), we can obtain the contribution (proportion explained) of the different factors of the instrument in the proposal. The proportions obtained were: (1) Factor 1 or Neurodidactics of Science category: 49%; (2) Factor 2 or Cognitive Psychology: 26%; and (3) Factor 3 or Neuroeducational category: 25%. Therefore, the influence of the conceptual change corresponds to the combination of Factors 1 and 3, which means 74%. Then, if the proposal obtains a moderate effectiveness of $(59 \pm 13)\%$, which means that only 44% conceptual change is achieved.

5. Conclusions

The possibility of making effective conceptual changes in science teaching is a growing trend today because of the number of misconceptions that students acquire through unguided prior experimentation or misinterpretation of algebraic physical expressions. The difficulty of eradicating them, where previous misconceptions remain, with mental inhibition being key, requires various effective actions to create better neural connections that are in conflict with the wrongly established ones.

A contextualized methodology that favors teaching–learning processes based on mathematics is necessary [73]. One solution is a methodology based on experimentation. When different resources are used, physics learning can be improved because it offers an open way to inquiry (IBSE), which results in more practical, perceptive, and visual teaching. However, total eradication of misconceptions is not possible if students do not construct an understandable descriptive and predictive phenomenon model (MBI), a shortcoming of IBSE. For that reason, our hypothesis work fails with respect to the modeling role. Models may mediate between theory, mathematics, and experimentation, according to Cascarosa et al. [79]. Conceptual modeling makes it possible to propose arguments to provide meaning to the phenomenon offering future predictions. Symbolic models are, in the first instance, a barrier to effective conceptual change due to the difficulty in obtaining the complete comprehension of the physical phenomena that is evidenced when other contexts are shown. We consider the importance of starting with other types of models, such as visual, descriptive, and gestural models, to test them to achieve a conceptualization of an understandable symbolic model.

Results show the importance of the DMCC model in the field of educational psychology [48], where we can confirm its guiding effectiveness. However, we consider the incorporation of more neuroeducational elements than these authors suggest. The message must be emotive and make use of motivational components such as questions, activities, hands-on activities, videos, and virtual simulators that awaken students' curiosity and hold their attention. However, it should be noted that separate actions, that is, working only on transdisciplinarity, do not make the construction of a totally effective conceptual change possible.

In conclusion, the results of this work report on the importance of incorporating the neuroscientific, psychological, and pedagogical advances (transdisciplinary learning) required to improve science teaching with respect to conceptual change. Each action is part of a chain that contributes to better learning, resulting in a neurodidactic approach where students discover behaviors and their causes, interact with their misconceptions, know their shortcomings and successes, and understand the reasons for natural phenomena through experimental inquiry and modeling in a positive and motivating environment, rather than simply solving equations or experimental inquiry based only on equations. Neurodidactic orientations in combination with model-based inquiry with an increase in experimental activities and resources that the IBSE method offers could be the possible way forward that science education is looking for, a new line of research that could be named Model Based Neurodidactic Inquiry (MBNI), a combination where our future works will support their effectiveness for an operative conceptual change.

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