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Article

Metacognitive abilities and the development of mathematical thinking

Las capacidades metacognitivas y el desarrollo del pensamiento matemático

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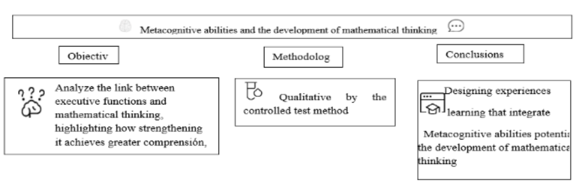
Abstract

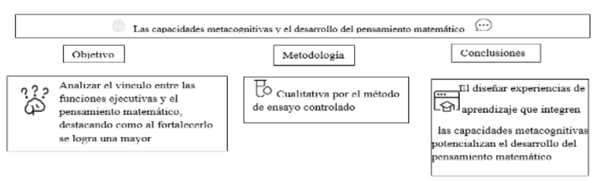
The development of mathematical thinking requires much more than the acquisition of content; it involves the activation of complex cognitive processes that allow us to analyze, plan, solve, and reflect on problematic situations. In this context, executive functions—such as working memory, cognitive inhibition, and mental flexibility—play a fundamental role in facilitating self-regulation, strategic decision-making, and adaptation to new problem-solving conditions. This article analyzes the link between executive functions and mathematical thinking, highlighting how strengthening them contributes to deeper understanding, logical reasoning, and the ability to model real-life situations. A didactic integration of these functions in the classroom is proposed, based on institutional competencies, to promote meaningful learning and the development of higher-order cognitive skills. The proposed research methodology was qualitative, using a controlled trial method.



Executive functions neurocognition

Resumen

El desarrollo del pensamiento matemático requiere mucho más que la adquisición de contenidos; implica la activación de procesos cognitivos complejos que permiten analizar, planificar, resolver y reflexionar sobre situaciones problemáticas. En este contexto, las funciones ejecutivas —como la memoria de trabajo, la inhibición cognitiva y la flexibilidad mental— juegan un papel fundamental al facilitar la autorregulación, la toma de decisiones estratégicas y la adaptación a nuevas condiciones de resolución. Este artículo analiza el vínculo entre las funciones ejecutivas y el pensamiento matemático, destacando cómo su fortalecimiento contribuye a una comprensión más profunda, al razonamiento lógico y a la capacidad de modelar situaciones reales. Se propone una integración didáctica de estas funciones en el aula, con base en competencias institucionales, para favorecer el aprendizaje significativo y el desarrollo de habilidades cognitivas de orden superior.
La metodología de investigación propuesta fue cualitativa por el método de ensayo controlado.



Funciones ejecutivas neurocognición.

Area: Promotion of frontier research and basic science in all fields of knowledge

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Introduction

Metacognitive abilities, also known as **executive functions**, are, as Bernal, 2023 mentions, a series of higher-order processes that allow individuals to focus and maintain attention, solve problems, adapt to different contexts, exercise self-control and discipline, etc. Metacognitive abilities play a crucial role in the development of mathematical thinking, including working memory, inhibition, cognitive flexibility, planning, and monitoring or self-control. These cognitive skills enable students to plan, organise, monitor, and solve mathematical problems efficiently, thereby regulating higher-level cognitive processes Bernal, 2024

Inhibition, as part of executive functions, is the cognitive ability to curb automatic impulses [impulse control], irrelevant thoughts [cognitive inhibition], inappropriate behaviours [behavioural inhibition], or filter out irrelevant stimuli to maintain the student's attention [attentional inhibition], thereby promoting adapted and conscious responses to a given situation. Diamond, 2013

The importance of inhibition in the development of mathematical thinking is that:
It facilitates the resolution of complex problems by avoiding classroom interruptions.It allows strategies to be evaluated before acting, optimising decision-making. It helps to maintain students' attention during prolonged or cognitively demanding tasks. Bernal, 2023

The second executive function that has an impact on mathematical thinking is *working memory*, which allows information to be temporarily retained and manipulated. It is essential for performing mental mathematical operations, following sequential instructions, or solving complex problems, acting as a temporary storage system that keeps information active while cognitive processing is taking place. Hernández, 2021

As Bernal, 2024 points out, another important executive function is *cognitive flexibility*, which facilitates changing strategy when faced with a mathematical problem, adapting to new rules, or correcting errors. This ability is fundamental to solving mathematical problems, as it arises from the prefrontal cortex and other specific areas of the brain, meaning that cognitive flexibility activates large areas of the brain, as Bernal, 2024

Suggests.

Planning within executive functions involves organising steps and selecting methods for solving problems. It is especially useful in long or multi-step tasks, such as calculations with fractions or algebra Bernal, 2024

Finally, metacognitive monitoring or self-control refers to the ability to review work, evaluate progress, and detect errors. It is crucial for validating mathematical solutions and adjusting strategies. Trías, 2024

As Pomanhuacre, 2024 describes, assessing executive functions in students involves using tools that allow for the observation and measurement of skills such as working memory, planning, inhibition, cognitive flexibility, and monitoring.
Buller, 2010 explains that among the tools for assessing executive functions are standardised neuropsychological tests such as:

The ***Stroop Test***, which assesses inhibitory control by asking the student to name the colour of a word that represents another colour.

The *Tower of London*: Measures planning and problem solving by organising coloured balls on rods.

Wisconsin Card Sorting Test: Assesses cognitive flexibility and the ability to change strategy in the face of new rules.

BANFE-2: A neuropsychological battery that assesses multiple executive functions in academic contexts.

Behavioural questionnaires, as Ramos, 2019 suggests, are other tools that assess executive functions and allow information to be obtained from different perspectives [teacher, family, student]. These include:

EFECO, which is a multi-source questionnaire that assesses eight indicators such as planning, working memory, inhibition, and emotional control.

BRIEF [Behaviour Rating Inventory of Executive Function]: Widely used in school settings to detect executive difficulties in children and adolescents.

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Torralvo, 2019, states that *dynamic and observational assessments* can be carried out in two ways: as *direct observation* in tasks that require organisation, problem solving or self-control, and as *performance analysis* in activities such as mathematical problem solving, reading comprehension or collaborative work.

Consequently, the above information raises the question: What activities promote executive functions in the classroom?

Valiente, 2024 proposes that executive functions are developed in mathematics classes through several alternatives.

I. *Solving contextualised problem situations* where the student: Plans the sequence of steps, identifies variables and evaluates different strategies to arrive at the result.

II. *Teaching sequences that involve decision-making*. An activity in which students must decide which method to use to solve a system of equations, justifying their choice.

III. Use of assessment tools where students determine their performance. *Self-assessment and co-assessment*.

IV. Maths activities or projects that require *planning* using a graphic organiser such as a Gantt chart or other process development tool.

V. Exercises with *changing rules*: the teacher gives the answer and the student must find the starting expression; halfway through the activity, the instruction is reversed, which promotes cognitive flexibility.

VI. Activities in which the student must research and summarise information within a certain time, thereby developing their **mental fluency and dual execution**.

VII. When *modelling real situations*, such as in problem-solving, the student requires **reasoning, working memory and decision-making**.

Benefits of applying activities that develop executive functions in upper secondary school students:

Among the most relevant benefits are:

- Improved sustained attention, i.e. the student can concentrate for longer periods of time.
- Strengthening of working memory, which facilitates following instructions and solving complex problems.
- Increased cognitive flexibility, thanks to which students adapt more easily to changes by finding alternative solutions.

It promotes planning and organisation in various collaborative tasks, where the contribution of ideas must be respected.

All of the above consequently reduces impulsivity and the series of errors that this premature response can generate, gradually producing **emotional self-control**. This is vital for upper secondary school students, who, in addition to their low level of prior knowledge, mostly suffer from **social anxiety**, which makes it impossible for them to participate actively in class, either individually or collaboratively in work teams.

The aforementioned activities also *allow students to develop resilience*, enabling them to face challenges more independently. Furthermore, they learn to monitor their own progress, generating independence in their academic performance; they improve their ability to make conscious and reasoned decisions and, therefore, increase their motivation for work and study, all of which contributes to their comprehensive training as individuals who will enter the workforce or the next academic level.

Development

As an intervention proposal, the following teaching sequence is proposed for a differential calculus class at the upper secondary level, including the development of **executive functions** as part of the teaching-learning process.

Subject: Differential calculus
Level: Upper secondary
Duration: 3 modules of 90 minutes
Topic: Derivatives as a rate of change.
Activity: *Cost changes: an easy decision?*

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Competencies to be developed: Mathematical logical thinking, problem solving, decision making.

Objectives:

- Understand the concept of the derivative as a rate of change.
- Apply the derivative in real economic situations.
- Develop executive functions such as planning, working memory, cognitive flexibility and inhibitory control.

Box 1

Table 1

Integration of executive functions

Executive function	Activity to be carried out
Planning	Draw up a timetable to solve an economic problem with derivatives.
Working memory	Retention and application of basic derivative formulae in different contexts.
Cognitive flexibility	Change of strategy in the face of problems with different types of functions.
Inhibitory control	Avoid errors in the calculation of derivatives by arguing the answer with coherent and consistent procedures.

Activities per module:

Module 1 Introduction and contextualisation.
Beginning: A contextualised problem situation in the economic sphere is presented.

Development: Through guided discussion, it is determined how the derivative can represent the change in costs.

Conclusion: Write a reasoned reflection on the decision-making process that would be established for the problem situation.

Module 2 Mathematical metacognition.

Beginning: Solve problems with polynomial and exponential functions in order to practise applying derivative formulas.

Development: Collaboratively, the team chooses a solution strategy that can be applied to the problem situation they are solving.

Closing: Co-evaluation of team members using an assessment tool that evaluates the reasoning and accuracy of the mathematical algorithm used to solve the exercises. Tekman

Module 3. Integrative project.

Beginning: Design of a research summary in which students argue for the modelling of the economic situation using derivatives.

Development: Presentation with a timeline, graphical analysis, and argumentation of decision-making.

Closing: Evaluation process using an assessment tool aligned with the competencies declared by the institution in question. Prot-Mandelbrot, 2020

The assessment tool proposed is a rubric that includes both mathematical performance and the development of executive functions.

Table 2 shows both the criteria to be considered and the expected achievement.

Box 2

Table 2

Rubric for evaluating the activity: Cost shifting - an easy decision?

Criterion	Expected achievement
Understanding of the concept of derivative.	Identifies and argues the reason for change located in the contextualised problem situation.
Application of the derivative concept.	Solves problems correctly and congruently, arguing the choice of the method to solve the situation.
Planning and organisation.	Presents a detailed chronogram for the sequence of steps to solve the integrative project.
Cognitive flexibility.	Changes strategy effectively when faced with new or more complex problems.
Working memory.	Uses correct formulas and algebraic procedures in functions with different characteristics.
Inhibitory control.	Collaboratively respects and contributes ideas to reduce procedural errors, which allows them to argue in an optimal way the mathematical decisions made.
Presentation of the final project	Communicates mathematical ideas clearly using graphical and symbolic representations.
Self-evaluation and reflection	Reflects critically on their process of understanding and application of the knowledge studied.

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It is important when carrying out any evaluation instrument to align the three elements that are being considered, in this case: Curriculum - Executive functions - Exit capacities of the institution. Thus, for this particular case, the alignment matrix set out in table 3 is obtained.

Box 3

Table 3

Alignment matrix

Element of the sequence.	Criterion of the rubric.	Indicator of the learner profile.
Introduction to the concept of derivative.	Understanding of the concept of derivative.	Understands the concept of the derivative as a rate of change and applies it in real contexts.
Project timeline.	Planning and organisation.	Develops logical and heuristic thinking to structure solutions.
Change of strategy in the face of various problems	Cognitive flexibility	Applies different strategies to solve complex mathematical problems.

This alignment must be considered to ensure that what is being assessed is consistent with what is stated in the curriculum and that metacognitive abilities or executive functions are indeed being correctly linked to the curriculum in question. Verzini, 2021

Results

Following the development of the teaching sequence and the subsequent application of the assessment tool, a higher percentage of students achieved a score above 8 in the diagnostic exit assessment applied to all upper secondary students at our institution.

Conclusions

The application of metacognitive skills, also known as executive functions, in mathematics classes strengthens learning, develops mathematical thinking, and enhances cognitive skills necessary for professional and academic life.

By designing activities that integrate various processes such as planning, cognitive flexibility, working memory, and inhibitory control, meaningful learning is achieved in students, promoting a reflective and functional experience.

These skills help students to independently and effectively tackle the challenges of academic thinking, such as problem solving, optimal decision making, and interpreting models in real-life contexts.

Integrating executive functions into mathematics lessons also enables students to apply knowledge critically, ethically, and strategically.

The development of executive functions is not simply a pedagogical innovation; it is a proposal for a more comprehensive education that is conscious of and connected to the demands of today's society.

Conflict of interest

The authors declare that they have no conflict of interest. The content of this article has no financial interest and is based on our experience as student trainers.

Contribution of the authors

Sánchez-López, Guillermina: author and editor of the article.

Salgado-Suarez, Gladys Denisse: method and style reviewer.

Conde-Sánchez, José Rubén: implementation and analysis of results.

Moreno-Aguilar, Ma. Antonia: implementation and analysis of results.

Availability of data and materials

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Background

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