Chapter

Executive Functions and the Improvement of Deductive Reasoning Abilities

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Abstract

Executive functions include online working memory's executive processes and other off-line functions such as task revising and planning. Deductive reasoning requires the construction and manipulation of representations and can be defined as a kind of updating process driven by reasoners' meta-deductive knowledge and goals. The main executive functions involved in reasoning are: (a) to focus and sustain attention; (b) to switch attention between component tasks; (c) to activate and update representations; (d) to inhibit automatic processes and discard irrelevant information; and (e) to revise reasoning process and result. A metacognitive training procedure on executive functions to improve deductive reasoning in secondary school students is presented. This procedure is mainly based on the application of two meta-deductive concepts (consistency, necessity) and two meta-deductive strategies (searching for counterexamples and exhaustivity). Our theoretical assumption is that efficiency on complex and novel cognitive abilities may be improved by specific instruction on the executive processes involved. The training procedure presented in this work highlights the special role that two executive functions (EFs) have in the improvement of deductive reasoning: inhibitory control of intuitive responses and revision of reasoning process and conclusions.

Keywords: executive processes, working memory, deductive reasoning, cognitive training, metacognition

1. Executive functions, working memory, and higher level thinking abilities

Pursuing intentions and reaching goals are central operations and principal activities of the human mind. Executive functions (EFs) are always required when goal-directed thoughts, intentions, and actions are complex and not automated. EFs hence constitute a crucial concept in Cognitive Neuroscience and Psychology; however, there is neither a consistent definition nor a common theoretical model of EFs. In fact, EF has frequently been considered as a difficult, elusive or even confusing concept (see [1–3]).

The origin of this conceptual confusion is diverse; being the first and most important, the twofold nature of EF, a neuropsychological concept, is centered mainly upon the activity of frontal cortices [4–7] that has also been adopted and widely used by Experimental Cognitive Psychology [8]. Apart from confirming the role of the frontal lobes in executive functioning, neuropsychological studies have shown that other cortical and non-cortical regions of the brain are also involved (see [9]). The development of diverse brain regions directly related with EFs is particularly relevant in infancy and early childhood, but it is also relevant in adolescence and continues till young adulthood (see [10]). The study of brain bases and developmental pattern of each EF are the present endeavors from the neuropsychological framework. From the experimental psychology perspective, a crucial task in order to eliminate or at least diminish conceptual confusion is to clarify the relationship between the EFs and two other basic psychological and cognitive concepts: working memory (WM) and higher level thinking abilities.

According to Baddeley and Hitch [11], WM is the cognitive system responsible for the temporary storage and manipulation of information. Thus, WM capacity refers to the number of items that can be recalled during a complex WM task. The multiple component model [11–13] includes two domain-specific storage structures or slave systems (the phonological loop and the visuospatial sketchpad), an episodic buffer that links the two prior components with long-term memory, and a central executive. The main component of the working memory system is the central executive: apart from coordinating the other components, it is in charge of the attentional control of information. Cowan's embedded-processes model [14] and Engle's general capacity model [15, 16], although neglect the existence of domain specific components in WM, share with Baddeley's model the idea of a domain general central executive whose main functions are to control attention and organize the flux of information by updating representations and inhibiting some other representations and processes. As we can see, for these models, EF is carried out within WM by means of a kind of central executive.

An important, related and very influential view by Miyake et al. [17] maintains a unitary perspective on EF, and postulates three interrelated but diverse EFs. Within the WM framework, these authors claim that the three executive components of EF are: (1) set shifting, the ability to flexibly switch back and forth between tasks or mental sets; (2) updating working memory representations, the ability to monitor incoming information for relevance to the task at hand and then appropriately update by replacing older with newer information; and (3) response inhibition, the ability to inhibit dominant, automatic, or prepotent responses.

Previous views share the idea that EFs are tightly related and, in fact, the diverse EFs can be considered a result of the acting of WM's central executive. A different view is that proposed by Diamond [18] from a developmental neurocognitive perspective. This author considers EFs as enabling the mental manipulation of ideas, managing novel information, inhibiting and resisting temptations, and staying focused during the execution of difficult tasks. A main feature of Diamond's conception is his proposal of two main types of executive functions, core and higher order EFs. The core EFs are three: (1) working memory, (2) inhibition or inhibitory control (IC), and (3) cognitive flexibility. As we can see, these three core EFs agree in a broad sense with those proposed by Miyake et al. [17]: working memory is related with the updating of WM representations and cognitive flexibility is related to task shifting or switching. This proposal differs from previous ones about the relationship between WM and EF: WM now is a part or component of EFs.

According to Diamond, higher order EFs, such as problem-solving, planning, and reasoning, are built from the core EFs. The proposal of higher order EFs is an important contribution of Diamond's theory. We agree that searching the solution in most complex and difficult cognitive tasks, like inferring the logical conclusion of syllogisms, solving mathematical problems, or playing chess may require, apart from the core executive functions, other specific executive functions. But

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Diamond's proposal confounds EFs with higher level thinking: problem-solving and reasoning are not exactly EFs.

Higher level thinking required to solve a problem or infer a logical conclusion demands the building of mental representations by integrating external and previously stored information, and their manipulation in a cognitive space: working memory (WM). According to the taxonomy of thinking formulated by Johnson-Laird [19], problem-solving is the kind of thinking activity that, on the contrary to the mere associative thinking of the wandering mind, is goal-directed and has a purpose or objective. Reasoning is a type of problem solving activity that has a clear and defined starting point, that is, the premises of the reasoning problem. From this definition, we can see that solving problems and reasoning certainly require EFs.

The thinking process in complex problem-solving and reasoning tasks involves various component subtasks that must be solved in a sequence and demands time to be rightly done. Individuals must keep their attention focused and the final goal of task activated throughout the entire process. Besides the initial construction of representations and the switching from one sub-task to the next, problem-solving and reasoning require individuals to update representations by activating long-term memory (LTM) information and to inhibit and discard representations and responses. The fulfillment of these complex cognitive tasks demands people to activate all their WM resources in a controlled and supervised way, that is, they require the activation of core EFs.

Besides core EFs, the complexity of computations and the extended in time character of sequential process often demand individuals to plan in advance and to revise at the end their behavior. They often require the acting of two higher order EFs: planning and revision. Problem-solving activities may or may not require revising the final solution, but it usually demands to elaborate a sequential plan of thinking activity. The problem of Tower of Hanoi, for instance, a task used as a test of planning, does not require revision because the correct final solution is obvious. However, in mathematical problems, as Pólya [20] showed and every Maths teacher may corroborate, both planning and revision are crucial. On the other hand, in deductive reasoning, planning is not often required, but reflecting on the drawn conclusion and revising it are the final necessary steps of the reasoning process (see, e.g., [21]).

The theory of EFs proposed by García-Madruga et al. [8] attempts to give account of these issues and to clarify the relationship between EF, WM, and higher level thinking (see **Table 1**). As we can observe, this proposal includes, besides the three classic EFs proposed by Miyake et al. [17] and Diamond [18], a fourth core EF: focusing and sustaining attention. This primary core EF is frequently forgotten in diverse theories but as teachers and educational psychologists know, and Baddeley [12] recognizes, the capacity to focus and direct attention is probably WM's most crucial EF. These four core EFs agree with the fourth component model proposed by Im-Bolter et al. [22] that, besides WM's mental activation capacity and mental inhibition capacity, also includes the executive functions of shifting and updating.

Apart from the core and higher order cognitive EFs, there is another executive function clearly involved in an individual's action: the emotional control of behavior. The relevance of emotional or "hot" EFs has been pointed out by diverse authors, particularly by Zelazo et al. [23] (see also [24]). The ability to modulate and regulate emotional responses underlies all human behavior, including higher level cognition.

We want to emphasize the tight relationships between EFs. These relationships change and develop with age and the consequent construction of a complex mind. As Miyake et al. [17] highlighted, a main characteristic of the core EFs is that they

Executive functions	General characteristics
• Focusing and sustaining attention • Switching attention • Activating and updating representations • Inhibition	• WM's online core EFs • Every complex and novel cognitive tasks demand their use
• Planning future cognitive behavior • Revision of task execution	• Off-line higher order EFs • Complex thinking activities as problem-solving and reasoning demand their use. They are carried out within WM and require to apply core WM's EFs
• Emotional control of behavior	• Emotional processes • They are involved in solving any kind of complex, novel, and difficult tasks

Table 1.
Main types of executive functions according to García-Madruga et al. [8].

are diverse but intimately related. The relationship between core and higher level EFs is also evident. Although planning and review have an early origin, EFs cannot develop adequately without a previous and substantial development of the core EFs. Higher order EFs require a previous ability to focus and maintain attention, to change attention between tasks, to update and connect with LTM, and to inhibit and resist automatic and intuitive responses and ideas [18]. Core EFs are in fact necessary preconditions of higher order EFs. The importance of IC is particularly clear in the executive functioning needed for complex thinking. Being able to devise a plan to solve a problem involves inhibiting unplanned but quicker responses; likewise, to be willing to revise a complex thinking activity implies to inhibit an early closing of the task. We will analyze in more depth later the role of IC in deductive reasoning tasks.

In the next sections, we focus on the training of working memory to improve higher level cognition and, particularly, how to improve deductive reasoning from the perspective of executive functions.

2. The training of WM and the improvement of higher level cognitive abilities

Over the last decades, research on the potential of cognitive training in different areas of cognition has been growing (see, e.g., [25]). Previous studies focused on induced cognitive and neural plasticity have evidenced the impact of training on both the structure and functioning of neural networks [26]. Consistent with this view, the effectiveness of cognitive training interventions is hypothesized to improve WM. The underlying idea is that if WM can be successfully strengthened by training, then generalization of training effects to other higher order cognitive skills or untrained tasks would also be expected. This idea is based on the assumption that boosting a domain-general cognitive mechanism would be an effective way to improve other related cognitive abilities and academic skills, such as comprehension and reasoning [27, 28]. The usefulness of training programs for education increases to the extent that improvements in WM functions might be particularly beneficial for individuals with poor WM skills and those who are at risk of learning difficulties associated with WM inefficiency (for reviews, see [29]). Consequently, the design of WM training procedures would be aligned with the improvement of complex learning and academic achievement (for a review, see [30]).

Most interventions aimed at improving WM and EF are based on the design and application of a process-based WM training regimen (i.e., training of specific cognitive processes without explicit strategy training) based on intensive and systematic practice of complex WM tasks (e.g., n-back task). These tasks are not only required for storage but also for monitoring current information, inhibiting irrelevant stimuli, updating relevant information for recall, and managing two tasks simultaneously. Frequently, the process-based interventions are oftentimes computerized and implemented as electronic games in which the difficulty of the task is gradually adapted to bring the participant to the limit of his or her WM capacity (e.g., Cogmed Working Memory Training Program [31]).

The results of different systematic reviews on the effectiveness of this type of intensive and systematic cognitive WM training programs indicate that they improve the performance on the trained tasks and other untrained WM tasks that share features close to those of the trained tasks (see [32–34]). Positive effects were found in children in early childhood education [35], school-aged children, and adolescents with typical development (for review, see [35, 28]), but also up to adulthood [36]. Positive effects were also found with students with cognitive deficits [37] or learning difficulties [30]. Therefore, these findings indicate that near-transfer effects seem to be possible after intensive WM training interventions.

One aim in many process-based WM and EF training interventions is not only to improve performance on WM skills but also to obtain transfer or generalizing effects that go beyond the trained domain (for a discussion, see [38]). To date, the evidence that supports the far transfer of WM training gains is quite mixed and not consistent across studies, so it has stimulated a debate concerning the transferability of WM training to higher level cognition (see [39]). Thus, whereas some researchers indeed do not find robust data that allow to affirm the effectiveness of training on WM to improve high-level cognitive functions (see [28, 33]), others reveal oftentimes near transfer to tasks that were not explicitly trained but share similar task features with the training tasks and sometimes even training-related benefits transferred to new tasks measuring a different construct (inhibitory control [40] and fluid intelligence [41]). For example, a recent study compared the effectiveness of two training programs, the first based on three WM tasks and the second on three IC tasks. The results evidenced that either WM or IC training leads to specific near transfer benefits in related trained tasks. However, only the IC training showed far transfer effects on a reasoning task (Raven's Advanced Progressive Matrices) [42].

More precisely, a recent review [43] suggests that the transfer effect of WM training to other cognitive abilities (fluid intelligence, academic skills, reading, or mathematics) is zero or, when observed, is minimal in typical development schoolchildren aged between 3 and 16 years. However, in a review focused on the effects of WM training on cognitive and academic skills, [30] authors showed limited but converging evidence for positive effects of process-based complex WM and executive control training on academic abilities (e.g., reading comprehension, arithmetic, and mathematical reasoning), particularly in children with cognitive deficits or learning difficulties.

An alternative approach to computerized WM tasks training regimes (see [31]) is that of those who argue that WM and EF can be improved by cognitive training programs integrated in the curriculum domains, so that the training is carried out in the classroom and in the context of learning tasks in which EFs are required (see [26, 44]). Some recent intervention studies suggest that this training perspective would provide wider benefits in educational settings than those obtained from training with computerized programs (see [45]). Although there are still scarce studies that try to improve EF in the context of learning activities that can be part of the curriculum, the results are promising to enhance academic skills in the domain of mathematics problem-solving [46], reading comprehension [47], and reasoning [48]. Moreover, other authors [49] found a maintaining effect of training-related benefits on WM updating and mathematics measures 3 months later. Nevertheless, further research is needed to improve our understanding of the underlying mechanisms that explain cognitive training gains.

As we can see, there is an interesting debate that does not seem to have irrefutable data. So far, the interventions that have been applied in previous studies greatly vary. Different factors possibly influence both training and transfer gains such as the nature of the training tasks and regime as well as age differences and individual differences [38]. Perhaps, the core question to be elucidated is what conditions give rise to transfer following WM and EF training. In that respect, different hypotheses have been proposed to explain transfer effects that are observed (or are not) after WM training. One proposal is that WM training enhances the specific processes within WM that are engaged by particular tasks: a process-specific transfer view. Consequently, transfer should only be expected when training and untrained tasks both place demands on the same processes (see [38]). Instead, a new perspective proposed by Gathercole et al. [50] maintains that transfer from WM training is a consequence of the development of new routines that must be implemented to accomplish a mental activity and are applied to new tasks. In other words, transfer only occurs when individuals have learned a new complex cognitive skill in the course of training and when that skill can be applied to a novel task with similar structure. The new "routine" is needed to execute existing processes in a new sequence when a task has complex and unfamiliar cognitive requirements. For example, new routines are required to perform visuospatial serial recall, complex span, backward span, and the updating tasks. Accordingly, the authors make two assumptions about WM training. First, training on unfamiliar WM tasks will lead to the development of new cognitive routines that control the execution of a sequence of cognitive processes required to perform the task components (e.g., encoding, maintenance, distractor processing, and retrieval). Second, the development of new routines depends on general attentional resources and they can only be applied to other tasks with similar structures; only then transfer will occur.

Our theoretical view maintains that an effective way to improve higher level cognitive abilities by WM training would be through the design and implementation of instructional programs. These programs must explicitly emphasize the activation of the WM's online core EFs—the general domain component of EC—in the context of new and complex cognitive tasks that involve executive functioning in a specific domain (reading comprehension, see [47]; reasoning, see [48]; and arithmetic, see [49]). We share the idea that there is a general mechanism underlying the transfer from complex WM tasks to higher level cognitive abilities such as reasoning, but we claim that there is also a specific mechanism bounded to the use of concrete tasks in the diverse fields. Thus, the activation of the specific mechanism involves both analyzing the role of EFs in the selected higher level thinking ability and selecting a set of relevant tasks to train in the higher level thinking field. Hence, our approach could also be aligned with the cognitive training as skill acquisition hypothesis [50] since we manage to improve higher level thinking abilities (e.g., deductive reasoning) through WM and EF training in the course of new and complex reasoning tasks. This aspect is an essential difference with respect to training programs particularly focused on intensive and systematic practice of complex WM tasks. The second main feature is that our training perspective is close to an ecological vision of cognitive training applied to education [51]. This broadens the view of recent theoretical debates on cognitive training and offers important educational implications for early interventions by designing instructional strategies that improve EF in the field of academic competences.

Overall, the findings suggest a promising line to design training programs for improving WM and EFs. Executive functioning training appears to transfer in some conditions, even though transfer appears to be narrow and some important questions remain [18, 52]. As these authors pointed out, a few principles seem to hold for effective training: (a) WM and EFs can be improved at any age through cognitive training and practice; (b) EF gains seem to depend on the amount of repeated practice; (c) EFs need to be continually challenged by training programs that keep incrementing task difficulty progressively as a person's skill improves; and (d) often those with the poorest EFs consistently gain the most from any program that improves EFs. Our view also emphasizes that appear justified to promote controlled processes through a metacognitive approach so that the participants receive guidance to recognize the involvement of the control processes in the activities of the training program, as well as to think about the importance to be aware of them.

On a more particular note with respect to a domain-specific training, some additional evidence comes from studies analyzing increased reasoning scores following different forms of WM training, particularly the specific impact of strategy-based WM training on reasoning. Ariës et al. [53] reviewed literature and concluded that there is no convincing evidence that content-based WM training alone (e.g., n-back training) improves adolescents' reasoning skills in education. However, a combined content-based WM-capacity- and reasoning-strategy training could serve as an effective instrument to enhance school-based reasoning achievements [54]. The authors highlight the important role of using content subjects such as history to improve reasoning through working memory [48]. This could indicate that transfer or training benefits seem to be more pronounced just in similar contents.

In this vein, in the next section of this chapter, we propose a training program with specific activities that have a relevant content for secondary students such as fallacies in ordinary context, detective's games, Sudoku tasks, false beliefs of individuals, and fake news on the Web. Our first task will be to analyze main theories and components of deductive reasoning ability and the function that EFs meet in the reasoning process.

3. Improving deductive reasoning by training the involved WM's executive processes

3.1 Deductive reasoning and executive functions

Deductive reasoning is a kind of thinking activity that has a precise starting point, a set of premises, and a goal, drawing a conclusion. In deduction, the conclusions do not involve any increase in semantic information. Also the process of connecting premises to the conclusion is ruled by logic, that is, the conclusions have to be necessary and consistent. Deductive reasoning, even the most elementary kind, is hence a complex phenomenon that requires individuals follow a sequential process that includes various steps and tasks and the passage from one to another. A second source of complexity comes from the need to temporarily store and update the diverse representations needed to carry out a deductive sequence. A third aspect is meta-deductive and consists of the necessity to keep track of this sequential process by keeping in mind the restrictions that rule deduction.

There are diverse theories of deduction, the two most important being that of "mental rules" and "mental models." According to mental rules theories, people possess a set of rules, a sort of "natural logic" from which they reach a conclusion by following a sequence of steps. Reasoning proceeds thus in a derivation process in which people apply a series of rules and procedures that allows them to yield a conclusion [55–56]. Deduction is thus an effortful process that depends on the complexity of the deductive sequence and is therefore clearly affected by reasoners' WM capacity. The fundamental prediction of mental rules theory is based on the number of rules or intermediate steps required for reaching a conclusion: the larger the process of deriving a conclusion, the greater the problem's difficulty.

The mental model theory of reasoning postulates that when individuals face deductive problems, they construct models or possibilities of the meaning of assertions consistent with what they describe [57]. The main assumption of model theory concerns the crucial role of WM in deduction: representing and manipulating models in order to reach a conclusion entail cognitive work and effort. Therefore, reasoners are likely to base most of their inferences from the initial and incomplete representation or models of the premises. The model theory's fundamental prediction is thus drawn from the number of models required for reaching a conclusion: the more the models, the greater the problem's difficulty. An inferential conclusion is necessarily valid if it holds in all the models of the premises. Finding a valid conclusion to complex problems requires that individuals build complete representations of premises and validate initial conclusions by searching for counterexamples that can make them false. In spite of their differences, rules and model theories agree that individuals' WM capacity affects deductive process and conclusions.

Apart from rules and models, there is a relatively new theoretical approach on thinking and reasoning in which WM plays a crucial role: dual-process theories (see [58–62]. These theories postulate the existence of two different types or systems of thinking: Type 1 (intuitive) and Type 2 (deliberative). Type 1 processing is considered fast, unconscious, associative, and not dependent on working memory (WM). Type 1 processing allows individuals to quickly access intuitive responses that can be valid, but it is also a source of pervasive mistakes. On the other hand, Type 2 processing is slow, conscious, controlled, and strongly linked to reasoners' WM as well as their thinking dispositions or mental styles. WM is thus a defining feature of analytical Type 2 processing.

Type 2 processing is required to solve complex reasoning problems, although this is not a sufficient condition for valid responses. Most dual-processing theories assume Type 1 processing yields intuitive responses that subsequent Type 2 deliberation may or may not modify. Stanovich et al. [63] claim that deliberative reasoning requires override Type 1 processing. Overriding Type 1 and activating Type 2 processing require an individual's executive control, as well as a propensity to think actively and resist the premature closing of problems. Executive control processes thus play a crucial role in analytical Type 2 reasoning processes [64–66].

From a mental model perspective, García-Madruga et al. [67] highlighted that central executive was the crucial WM component in the explanation of propositional reasoning performance. In order to confirm the role of executive processes in deductive reasoning, these authors used two WM central executive measures: the classical Reading Span Test (RST) [68], in which people have to remember the final word of a series of sentences; and a new test that loads more on the central executive since it demands that people solve and remember the word solutions of a series of verbal anaphora. These authors found that higher WM participants, as opposed to lower WM participants, gave reliably more correct Type 2 responses and fewer intuitive (Type 1) responses to the deductive problems, particularly on the new more complex anaphora measure. Likewise, studies with syllogistic reasoning problems have borne out the crucial role of WM, particularly the executive processes [69], as well as its relationship with the two types of reasoning processes [70].

Mental model's explanation for the difficulty of deductive inferences easily accommodates the dual process view: Type 1 reasoning corresponds to the initial conclusions, whereas the cognitive work of constructing complete representations and searching for counterexamples corresponds to Type 2 reasoning.

In a recent work, Thompson, Prowse Turner, and Pennycook [71] have pointed out that Type 1 processes are accompanied by a metacognitive experience, called the feeling of rightness (FOR), which can signal when additional Type 2 analysis is needed. They found a robust relationship between the low FOR and the activation of Type 2. More recently, Bago et al. [72] tried to activate Type 2 thinking using a second guess paradigm in the bat-and-ball problem:

> *"A bat and a ball together cost $1.10. The bat costs $1 more than the ball. How much does the ball cost?"*

This problem is included in the cognitive reflection test developed by Frederick [73] that allows to evaluate individuals' ability to override Type 1 processes and be able to give a hard Type 2 response. Bago et al. [72] asked participants to give a first answer to this problem and rate its difficulty. The most probable response was the intuitive answer "10 cents." Participants also show a high confidence in their wrong response. In a second guess, most of participants also err, but their wrong answers were smaller than the first attempt. Moreover, participants were now less confident in their responses. These results indicate that although reasoners did not know the correct answer "5 cents," they realized that the correct answer was smaller than the intuitive "10 cents." These results could be explained by the feeling to rightness (FOR) and highlight the importance of metacognition in the searching for Type 2 responses [74]. Furthermore, it is necessary to inhibit the first intuitive response (Type 1) to give the correct response. As all EFs, this ability is related to the prefrontal cortex, especially the anterior cingulate cortex (ACC [75]).

In another well-known task, the Wason selection task, four cards (A, P, 7, 2) with a letter on the one side and a number on the other side, people are asked to turn over the cards that false the rule: "If there is a vowel on the one side, then there is an odd number on the other side." People use to choose A and 7. This bias is called the perceptual matching bias because people choose the mentioned items [76]; however, the correct answer is A and 2, that is, people need to inhibit their first answer and redirect attention to the alternative response. Houdé et al. [77] ran an inhibition control training to avoid the matching bias and found a shift of brain activation using the technique of PET from the posterior part of the brain on the pretest to a left-prefrontal network on the posttest, that is, from perceptual-related areas to WM-related areas. According to Houdé and Borst [78], to inhibit heuristic responses, Type 1 is the critical process that allows to reason logically (Type 2; see also [63]); however, this is highly dependent on the maturation of the prefrontal cortex.

Due to the importance to override dominant or prepotent responses and activate Type 2 responses, we propose to work deeply the inhibition control in the deductive training. Therefore, to draw a conclusion in a complex deductive problem, the necessary EFs are: (1) to focus attention and activate all cognitive resources; (2) to switch attention from one cognitive task to another, that is, to pass from one step to the next in a deductive sequence; (3) to activate and use knowledge stored in LTM in order to update WM representations; (4) to inhibit initial intuitive responses and discard irrelevant information; and (5) to revise intuitive responses in a controlled metacognitive way. For this reason, we propose to include all of them in an integrative reasoning training.

3.2 A metacognitive training procedure to improve deductive reasoning

With age, children are increasingly able to understand and infer valid conclusions from propositional assertions. According to model theory, the developmental pattern is related to the number of true possibilities contained within each assertion: children first interpret conjunctions, and then disjunctions and conditionals. First defended by model theory, this pattern of acquisition is directly related to an increase in WM capacity during childhood and adolescence [79–81].

Due to its special relevance, researchers have paid particular attention to the development of conditionals. Children's interpretation of conditionals, such as "If it rains then Eliza uses an umbrella," seems to be based mainly on the construction of only one true possibility, the initial one that affirms both clauses: the antecedent and the consequent (it rains and Eliza uses umbrella); conditionals are thus interpreted as conjunctions. Older children and preadolescents are also able to construct and use a second possibility in which the antecedent and the consequent are negated (it does not rain and Eliza does not use umbrella); that is, at this age, most individuals make a biconditional interpretation of "if" assertions. Finally, only late adolescents and adults are able to build the third true conditional possibility which negates the antecedent and affirms the consequent (it does not rain and Eliza use umbrella). A complete interpretation of conditionals is thus a late developmental acquisition (see, e.g., [82–84]).

A similar developmental pattern was found in the interpretation and reasoning from syllogistic premises with abstract content by García-Madruga [85]. In this study, students of four academic levels (seventh graders, ninth graders, eleventh graders, and first university course) were asked to interpret the four syllogistic premises by means of Euler diagrams. They were also asked to solve a set of syllogistic problems of various difficulties. The percentage of mistaken interpretations of the four types of syllogistic premises decreased with age, from seventh graders (12 years old) to university students (18.9 years old), although the percentage of incomplete representations (i.e., correct but not complete responses) was very high in both adolescents and adults. For instance, only a half of adolescents (eleventh graders, 16.5 years) and young adults (university students,) were able to correctly interpret universal affirmative assertions, such as all A are B. The percentage of correct responses in the syllogistic reasoning task also increased with age, although the most difficult problems (i.e., those that are exhaustive and require searching for counterexamples) were also very difficult for older students.

WM's capacity is not, however, the only variable that explains the development of reasoning abilities throughout childhood and adolescence. As Inhelder and Piaget claimed [86], there are some specific changes in reasoning abilities during preadolescence and early adolescence, between 12 and 15 years. According to Moshman [87], these new abilities must be interpreted as metalogical or metadeductive. In other words, they involve an individual's capacity to reflect on one's own logical activity itself and to distinguish between logical validity and reality. Metadeductive abilities include the implicit understanding of the logical system and its basic concepts of necessity and validity, as well as the explicit use of this knowledge by applying metalogical strategies, such as searching for counterexamples. There is a gradual acquisition of metalogical understanding during preadolescent and adolescent years: from 11 to 12 years, preadolescents begin to understand the concepts of necessity, consistency, and the validity of logical conclusions [81]. However, preadolescents and adolescents cannot think about the logical system as a whole and take it as an object of knowledge. Explicit metalogic capacity only becomes possible in late adolescence and adulthood when individuals are already able to apply metadeductive strategies in solving deductive problems.

Velasco and García-Madruga [88] investigated the development of metalogical understanding and logical reasoning using abstract syllogistic premises during preadolescence and adolescence (between seventh and twelfth graders). They confirmed that a third of seventh graders (12.5 years old) were still unable to understand the logical concepts of necessity and validity correctly. Likewise, these authors found that only a half of twelfth graders (17.8 years old) used the strategy of searching for counterexamples spontaneously. Given the developmental pattern, we have briefly described that the instructional program of WM executive processes to improve deductive reasoning cannot be applied before adolescence.

Our theoretical explanation on the relationship between executive functions and thinking allows us to design a procedure for training deductive reasoning with adolescents. Deduction involves the correct interpretation of premises, that is, building a representation of premise meaning and manipulating these representations in order to arrive at a necessary conclusion. The comprehension of premises is not specific to reasoning, but the goal-oriented sequential task of manipulating representations is. This sequential task is performed in WM and can be defined as a specific kind of updating process. It is not driven by the input, as in the case of ordinary reading comprehension, but instead is a top-down updating process driven by reasoners' meta-deductive knowledge and abilities. They include the following tenants that: (a) premises and conclusions must be consistent; (b) a valid conclusion must be necessary; (b) a useful strategy to reach a valid conclusion is one of searching for counterexamples; and (d) when looking for a necessary conclusion, reasoners should never quit before evaluating all the possibilities (i.e., their work must be exhaustive). In order to reach a valid conclusion in complex reasoning problems, individuals have to carry out a sequential top-down updating process that includes the following stages (see [55, 89]):

1. **Comprehension of premises**. Reasoners have to understand deductive premises in depth. They have to search for and be aware of the different possibilities of the meaning of sentences. These possibilities must be consistent.

2. **Integration of premises and formulation of an initial conclusion**. This initial putative conclusion is likely not necessary; it is based only on a partial set of possibilities. Reasoners have to recognize that this initial response is likely invalid and therefore they should inhibit it.

3. **Validation**. This revision phase is particularly important, and it takes time and can be very demanding from a cognitive and motivational perspective.

    a. Applying a strategy of searching for counterexamples involves activating LTM knowledge, using diverse possibilities of the meaning of sentences, and combining these possibilities in order to falsify the initial conclusion.

    b. Validation may be completed in two cases only: (a) a new conclusion without counterexamples has been found; and (b) an exhaustive analysis of the meaning of sentences does not find a necessary conclusion.

The four main objectives of the training program were to improve reasoners': (1) comprehension of deductive assertions and premises; (2) meta-deductive knowledge and revision strategies; (3) inhibitory control to avoid intuitive responses and a premature closure of the task; and (4) metacognitive monitoring of the updating process by means of explicit instruction and repeated practice. The program is designed to be applied to 15–16 years old adolescents (tenth grade level) and consists of 12 sessions of 50 min, and nine different tasks (see **Table 2**). The first session was focused on explicitly laying out the theoretical basis of the instructional program, that is, the role of executive and metacognitive processes in reasoning. In this session, we explained the sequence of deduction, the role of diverse executive processes, and the difference between deduction and metadeduction. The presentation of the trained EFs was illustrated with a specific icon for each executive process (see **Table 3**).

We also highlighted the "feeling of rightness" (FOR) perspective in the activation of Type 2 processes and the identification of fallacies: when the FOR is low, Type 2 processes tend to activate. This perspective has an interesting instructional corollary: to improve the activation of Type 2 training must include instructional experiences that diminish people's FOR when facing fallacies. The following is an example of the specific reasoning contents presented:

> *Pablo is not very good in Maths. Julián, his teacher, has been talking with him and has told him that if he works harder then he will pass the exams. In summertime, after the end of exams, we met Pablo and asked him whether he passed the Mathematics exam or not. He told us:*
>
> *"The teacher is a liar, I did not work harder but I passed"*
> *What do you think? Is the teacher a liar? Why?*

An explicit explanation of how we reason, including a brief version of the deductive sequence, was then presented.

Sessions	Tasks
Session 1	**Introduction. Executive processes in reasoning** The sequence of deduction. Deduction and metadeduction Fallacies and the "feeling of rightness" What are we going to do? From lazy thinking to active thinking The five executive processes we are going to train
Sessions 2 and 3	**Reasoning task 1**. Consistency **WM task 1**. Analogies **Reasoning short task 5**. Fallacies and games
Sessions 4 and 5	**Reasoning task 2**. Necessity **WM task 2**. Anaphora **Reasoning short task 5**. Fallacies and games
Sessions 6 and 7	**Reasoning task 1 and 2**. Consistency and necessity **WM task 3**. Operation **Reasoning short task 5**. Fallacies and games
Sessions 8 and 9	**Reasoning task 3**. Searching for counterexamples **Reasoning task 4**. Exhaustivity **Reasoning short task 5**. Fallacies and games
Sessions 10 and 11	**Reasoning task 3**. Searching for counterexamples **Reasoning task 4**. Exhaustivity **Reasoning short task 5**. Fallacies and games
Session 12	**Recapitulation** Applicability and usefulness Rationality and fallacies in ordinary life

Table 2.
Description of sessions and training tasks in the reasoning program.

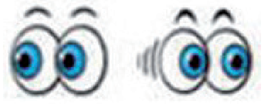
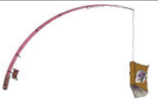
Executive function	Icons	Tasks tapping into each executive function
Focusing		*Comprehension of premises*, *integration of premises*, anaphora, analogies, operation, necessity, consistency, fallacies and games
Switching		*Comprehension of premises*, *integration of premises*, anaphora, analogies, operation, necessity, consistency, fallacies and games
Connection with knowledge		*Comprehension of premises*, *integration of premises*, anaphora, analogies, operation, necessity, consistency, fallacies and games
Semantic updating in WM		*Comprehension of premises*, *integration of premises*, anaphora, analogies, operation, necessity, consistency, fallacies and games
Inhibition (IC)		*Comprehension of premises*, *integration of premises*, anaphora, analogies, operation, necessity, consistency *validation*, searching for counterexamples, exhaustivity, fallacies and games
Revision		*Comprehension of premises*, *integration of premises*, *validation*, searching for counterexamples, exhaustivity, fallacies and games

Table 3.
The executive processes trained, their icons, and reasoning stages (in italics) and tasks.

The final session of the program was that of recapitulation: the main aspects of training as well as its utility for diverse situations and intellectual contexts were described and discussed with participants. Among a few of these contexts, practical examples were presented on daily situations, politics, argumentation, and academic subjects in the social and natural sciences, and that of mathematics.

The training tasks used in the program were three WM tasks and five reasoning tasks. All the training sessions, except first and last ones, ended with a reasoning short task that presented to secondary students some fallacies to be identified, as well as various activities connected with their interests, such as Sudoku and detective games or searching for fake news on the web.

The instructional techniques used were the same as those of the reading comprehension program: direct instruction, modeling, and guided and independent practice. The three WM tasks were the analogy, anaphora, and operation tasks. In these tasks, participants have to solve a series of verbal analogies, anaphora, or simple arithmetic problems and remember the solution to each of them. These tasks are complex dual tasks that involve the repeated operation of solving an inferential problem, as well as storing and maintaining activated in WM its solution. Therefore, WM tasks require the activation of the four core executive processes: participants must focus and switch attention, update and connect to LTM to infer the solution to be remembered, and to inhibit wrong responses to the inference task. Most importantly, these WM tasks possess a very similar structure to reasoning tasks. Although a more precise analysis would be necessary, we think that these tasks probably involve some of the cognitive routines also included in deductive reasoning tasks (see [50]).

In reasoning tasks, we used an adaptive learning procedure, that is, in each task, problems were presented in an increasing order of difficulty. Participant's behavior throughout each task was recorded. The four core executive processes are involved in each of the training tasks and problems. Moreover, the sequential task of drawing valid deductive inferences requires the active monitoring of reasoning process, inhibiting a premature closing of the task and revising any conclusions reached. In **Table 3**, the involvement of diverse EFs in each stages and tasks of reasoning can be observed. As mentioned above, the five reasoning tasks, particularly task 5, include activities that address issues, contexts and contents of specific interest for secondary students. Reasoning tasks 3 (searching for counterexamples) and 4 (exhaustivity) are complex revision tasks that demand more time and sessions than reasoning tasks 1 (consistency) and 2 (necessity). The procedure to improve deductive reasoning has not been yet empirically tested, although a few prior pilot studies for evaluating the materials and procedures have been carried out. The predicted effects of training procedure would be checked in various deductive tasks, different to those used in training, as well as other reasoning tasks like fluid intelligence test, mathematical problems, and social reasoning tasks. Given the crucial role that WM and EFs have in education (see [1]) and the tight relationship between reasoning and academic achievement (see [90]), we expect that our procedure yields an improvement in student's performance at school.

4. Conclusion

Our theoretical view on executive processes allows us to develop specific procedures to improve thinking abilities. We have designed and checked a procedure to improve reading comprehension in primary school students. We think that as in the case of reading comprehension, a synergic confluence of the EFs and cognitive training perspective with the theoretical analysis of deductive reasoning is possible. The metacognitive procedure to improve deductive reasoning presented in this chapter aims to integrate our claims regarding executive processes and the feasibility of its training, with an explanatory framework of deductive reasoning based mainly on mental models, dual processing and metadeductive approaches. As we have briefly described, researchers have claimed and construed the crucial role that WM's executive processes have on people's deductive performance. In order to instruct and improve deduction we need to reach a synthesis between these two perspectives. Our procedure attempts to provide such a synthesis and, for this reason, it deserves to be empirically tested. Apart from the predicted increase of deductive reasoning abilities, there is also a predicted transfer benefit in the improvement of students' learning and academic achievement.

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