
THEORETICAL REVIEW

The role of executive function in the construction and employment of scientific and mathematical concepts that require conceptual change learning

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ABSTRACT

We discuss the theoretical rationale and behavioral evidence for the involvement of Executive Function (EF) skills in the construction and employment of scientific and mathematical concepts that require conceptual changes for their formation. It is argued that conceptual changes such as knowledge revision and the formation of new and counter-intuitive concepts require extensive attention, increased comprehension monitoring, adoption of multiple perspectives, comparison of new information with prior knowledge and inhibition of prior knowledge and thus are very likely to recruit the EF skills of working memory, shifting and inhibition. The results of empirical research have shown that EF skills are indeed recruited in the construction and employment of such tasks. Particular emphasis has been paid to the role of inhibition which seems to be specifically recruited in tasks in which the use of a scientific or mathematical concept contradicts an initial concept which must be rejected. Further research is needed with an emphasis on training studies to investigate the effects on student learning of different kinds of interventions that integrate EF training with the teaching of science and mathematics.

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1. Introduction

The complex knowledge involved in the construction and employment of science and mathematics concepts is represented in distributed networks located in different parts of the adult brain, making executive control indispensable for deciding what to access and what to suppress (Allan et al., 2014; Jacob & Parkinson, 2015). Executive function (EF) skills such as working memory, task switching or shifting, and inhibitory control are fundamental for engaging in the goal-directed control of thought and behavior, for managing existing knowledge networks, and for the inhibition of learned responses in order to acquire the new and counter-intuitive concepts of currently accepted science and mathematics.

Functional magnetic resonance imaging studies have established a link between EF skills and well-defined areas of the prefrontal cortex (PFC) and specifically the dorsal lateral prefrontal cortex (DLPFC) and the anterior cingulate cortex (ACC) (Fuster, 2015). Developmental studies indicate that even infants can use aspects of the frontal system to suppress inappropriate responses in order to support task appropriate behavior (Bell & Fox, 1992). Nevertheless, there is a protracted development of these regions which has been interpreted to support the creation of increasingly more abstract goal representations. These abstract goal representations enable children and adolescents to improve their cognitive control both in reaction to environmental signals and in pro-active preparation for such control (Munakata, Snyder, & Chatham, 2012).

EF skills have been found to be significantly related to academic achievement even when intelligence and prior knowledge are controlled for (for meta-analyses, see Allan et al., 2014; Jacob & Parkinson, 2015), including performance in reading, (Kieffer, Vukovic, & Berry, 2013; van de Sluis, De long, & Van Der Leij, 2007); in math (Blair & Razza, 2007; Bull, Epsy, & Wiebe, 2008; Siegler & Pyke, 2013; Vukovic et al., 2014); and in science (Mayer et al., 2014). This is not a surprising result in view of the importance of persistent attention, working memory and cognitive flexibility for success in classroom learning (Lyons & Zelazo, 2011; Zelazo, Blair, & Willoughby, 2017).

In this article, we focus specifically on a subset of academic tasks that use science and mathematics concepts which required conceptual changes for their construction. In the pages that follow we will define what we mean by conceptual changes in science and mathematics and describe the theoretical rationale and behavioral evidence for the involvement of EF skills in their construction and employment.

2. Conceptual changes in the learning of science and mathematics

Conceptual change research investigates the kind of learning that requires considerable changes in existing knowledge and the formation of new concepts, new representations, and

new ontological categories. A great deal of learning can be accomplished by incorporating new information to existing conceptual structures. However, sometimes the acquisition of new information cannot be simply added on what is already known; in fact, it might come in direct conflict with what is already known. In these cases, learning requires the revision of prior knowledge. Often the Piagetian terms 'assimilation' and 'accommodation' have been used to refer to the distinction between adding new information to existing knowledge structures as opposed to altering or revising existing knowledge structures (Piaget, 1985). Conceptual change research has been instrumental in describing the different kinds of knowledge revision that take place with development and learning, such as the differentiation of concepts, (e.g., the differentiation of the concept of *heat* from *temperature*, Wiser & Carey, 1983), the re-assignment of a concept to a new ontological category (e.g., the re-assignment of the concept of *force* from the category of substances to the category of interactions, Chi, 2013); and of the creation of new concepts, new categories or new representations. For example, the construction of even the simple concept of the spherical earth and the explanation of the day/night cycle require considerable conceptual changes over young children's initial geocentric representation of the Earth as a flat physical object with a moving Sun and Moon located in the sky above and hiding behind mountains or clouds (Vosniadou & Brewer, 1992, 1994). These conceptual changes require, amongst others, the creation of new counter-intuitive representations of the Earth, the Sun and the Moon, in a heliocentric solar system and the re-categorization of the Earth in the category of astronomical as opposed to non-astronomical objects (Vosniadou, 2013; Vosniadou & Skopeliti, 2013).

The construction of scientific and mathematical concepts often requires conceptual changes in prior knowledge because children form initial understandings of the physical and social world on the basis of their observations and lay culture before they are exposed to scientific and mathematical concepts. These experientially based, initial constructions are usually very different from the currently culturally accepted scientific and mathematical concepts, which can be rather counter-intuitive. Let us not forget that it took hundredths of years of research and several scientific revolutions to establish many of the scientific concepts which students are taught in schools today. As a result, the learning of science and mathematics can be quite taxing for students who must undertake considerable conceptual changes in their initial conceptual structures in order to achieve it (Carey, 1985; Chi, 2013; Vosniadou, 2013).

For a long time, conceptual change researchers implicitly assumed that when scientific explanations and theories are acquired, they replace initial understandings. Although some researchers had suggested that this may not be the case some time ago (e.g., Caravita & Halldén, 1994; Inagaki & Hatano, 2004), it is only recently that a body of evidence started to be accumulated demonstrating the co-existence of initial

understandings and scientific explanations in a number of different knowledge domains (physics, biology, medicine, psychology, mathematics), different cultures (American, European, African, indigenous populations), and using different methodologies (interviews, questionnaires, reaction time studies, neuroimaging).

The bulk of this evidence comes from a series of psychological studies which investigate the employment of science concepts after they have been constructed. These studies have shown that both children and adults, across many different cultures, frequently use, amongst others, both natural and supernatural explanations of phenomena such as creationist vs. evolutionary accounts of the origin of species (Evans & Lane, 2011), biological vs. supernatural explanations for the transmission and cure of serious illnesses (Legare & Gelman, 2008, 2009), supernatural vs. scientific accounts of death (Legare et al., 2012), and dualistic vs. materialistic explanations for the mind (Preston, Ritter, & Hepler, 2013).

Further evidence comes from reaction time studies which show that both children and adults are slower (and sometimes less accurate) in tasks that require reasoning in situations in which the experimental stimuli are consistent with scientific but inconsistent with initial conceptions compared to cases where scientific and initial conceptions are consistent with each other. For example, Babai and Amsterdamer (2008) found that ninth graders were less accurate and slower when they classified as solids non-rigid solids (e.g., wax) and powders (e.g., salt) compared to rigid solids (e.g., diamonds), and as liquids dense liquids (e.g., honey) compared to runny ones (e.g., milk). Similarly, Potvin, Masson, Lafortune, and Cyr (2014) showed that secondary school students take more time to decide which of two objects will sink when the correct response involves the lighter as opposed to the heavier object, going against the common misconception that 'heavier objects sink more'. These results have been interpreted to indicate that initial (also known as naïve or intuitive) concepts co-exist with scientific ones and interfere in their employment. It has also been suggested that the extra time required in the employment of such scientific concepts is used to inhibit the interfering initial concept.

In another series of experiments Kelemen and her colleagues examined whether under speeded conditions adults endorse teleological – or purpose-based – explanations of natural phenomena of the kind that are commonly given by children. Children often attribute intentional causality to explain natural phenomena and endorse teleological over physical-causal explanations, such as that rocks are pointy so that animals won't sit on them. Adults overgrow such purpose-based initial explanations but do not seem to completely replace them with physical-causal ones. Kelemen and Rossett (2009) found that undergraduates accepted significantly more scientifically unwarranted teleological explanations (such as that the sun radiates heat because warmth nurtures life) under speeded conditions compared to moderate or un-speeded conditions, concluding that schooled adults preserve the tendency to see purpose in nature and to exhibit

this tendency when executive control is poor. In subsequent research Kelemen, Rottman & Seston (2013) showed that academic scholars in the humanities as well as actively publishing physical scientists in leading US universities, who explicitly rejected unwarranted teleological explanations about nature, nevertheless endorsed them under speeded conditions, indicating that there is a threshold to the revision of agentive and intentional conceptualizations of nature. Shtulman and Valcarcel (2012) also tested the co-existence hypothesis not in one but in 10 different domains of knowledge from the life sciences to the physical sciences to mathematics. Their results showed that undergraduates verified statements whose truth value differed across naïve and scientific theories significantly less accurately and more slowly than statements whose truth value was the same across both theories, suggesting that the co-existence of naïve and scientific theories extends across multiple domains of knowledge.

Similar results have been obtained in the domain of mathematics learning. In two experiments, DeWolf and Vosniadou (2015) investigated the effects of the whole number bias in timed fraction magnitude comparison tasks with skilled adults. The whole number bias refers to the application of whole number knowledge in situations in which this is not appropriate (see Ni & Zhou, 2005). The results showed that both accuracy and response time depended on whether the fraction magnitudes were consistent or not with whole number ordering indicating that even skilled adults do not have direct access to the fraction magnitudes on the number line when the distance between the fraction pairs is very small. These results are consistent with the findings of other experiments which show that the whole number parts of which fractions are composed (the numerator and denominator) interfere with their processing (see Meert Grégoire, & Noël, 2009, 2010; Obersteiner et al., 2013; Vamvakoussi, Van Dooren, & Verschaffel, 2012). In a series of studies that used intensive training Kallai and Tzelgov (2009, 2012) found that despite that fractional values could be learned to be processed efficiently, the process did not reach automaticity. On the contrary, the whole number fraction components interfered and in fact dominated the automatic processing.

3. The role of EF skills in the employment of science and mathematics concepts which require conceptual changes

If initial concepts co-exist with scientific and mathematical concepts, it makes sense to hypothesize that the employment of such concepts should depend on cognitive processes that require continuous comparisons between them, the adoption of different perspectives, the adjustment of decision making to changing contexts, the ability to keep information in working memory, extensive attention, and the inhibition of initial concepts when necessary. All these cognitive processes depend heavily on the recruitment of EF skills such as working memory, shifting, and inhibition. Working memory would be required to keep the two concepts/representations/explanations in mind and continuous

shifting to compare them and decide which one to use in the current context. Finally, inhibitory control would be needed to suppress the inappropriate representation.

Although there are good theoretical reasons to hypothesize that all EF skills would be recruited in the construction and employment of science and mathematics concepts, most of the empirical research has focused on the investigation of the role of inhibition, for reasons that are explained below. In the pages that follow the relevant research will be reviewed.

3.1 The role of inhibition

Inhibitory control has been specifically related to conceptual change in science and mathematics learning because the construction of new representations and new ontological categories in these areas often requires overcoming the strong pull of initial belief systems (Babai, Younis, & Stavy, 2014; Masson et al., 2014; Van Dooren & Inglis, 2015). Preliminary results coming from neuroimaging studies indicate that there might be differences in brain activation between novices and experts when they must evaluate counter-intuitive scientific stimuli. Experts seem to activate brain areas involved in inhibition, indicating that they are actively suppressing contradictory evidence to answer scientifically (Fugelsang & Mareschal, 2014). Masson et al., (2014) used functional magnetic resonance imaging (fMRI) to compare brain activation in experts and novices when evaluating the correctness of simple electric circuits. The results showed that experts more than novices activate brain areas involved in inhibition when evaluating erroneous stimuli, suggesting that they are suppressing misconceptions encoded in the neural networks of their brain.

Behavioral studies in mathematics learning have also shown that inhibitory control is significantly related to general mathematics achievement (e.g., Blair & Razza, 2007; Bull & Scerif, 2001; Espy et al., 2004; St. Clair-Thompson & Gathercole, 2006; Siegler & Pyke, 2013). Siegler and Pyke (2013) found relations between general mathematics achievement and inhibitory control in sixth and eighth grade students, while Gilmore et al. (2013) found that inhibition was related to mathematical procedural knowledge in younger participants and conceptual knowledge in older participants (see also Cragg et al., 2017).

3.2 Behavioral evidence for the recruitment of inhibition in conceptual change processes

Is there any behavioral evidence to support the hypothesis that inhibition is recruited in the employment of science and mathematics concepts which require conceptual changes for their construction? An explicit link between inhibition and a type of conceptual change learning has been shown in an experiment which investigated the employment of linear vs. logarithmic number estimations in adults (Laski & Dulaney, 2015).

Research has shown a change from logarithmic to linear number estimations with age. For example, kindergarten children produce number line estimates of numbers ranging

from 0 to 100 that are better fit by a logarithmic function than by linear one, while second graders produce number line estimates that are better fit by a linear function (Booth & Siegler, 2006; Opfer & Thompson, 2008). The development of new representations of numerical magnitude has not been treated as an instance of conceptual change learning by Sielger and his colleagues, but it does meet the definition of conceptual change discussed earlier, namely, learning that requires the substantial revision of prior knowledge, and the creation of new representations.

Laski and Dulaney (2015) argued that adults activate both linear and logarithmic number estimations and that the employment of a linear numerical representations requires the suppression of the interfering logarithmic one. To test this hypothesis, they compared the performance of adult participants in an easy and familiar number line estimation task, with standard endpoints involving powers of 10 (0-1,000) and one with unfamiliar, non-standard endpoints (364-1,364). The results showed that the participants generated estimates with greater fit to the logarithmic function on the non-standard number line task compared to the standard one. This result was interpreted to support the hypothesis that adults possess both kinds of representations and activate the initial, logarithmic one when confronted with difficult tasks. The results also showed that the adults' ability to inhibit numerical responses in a number-quantity Stroop task was related to the degree to which their estimates fit the logarithmic function in the case of the non-standard number line task, even when the tendency to use logarithmic representations on number lines with standard number line tasks was controlled for.

In summary, the results of the studies reviewed so far show longer reaction times in the employment of science and mathematics concepts when they are inconsistent as opposed to consistent with an initial concept that contradicts them. This result suggests that the participants need the extra time to inhibit the interfering initial concepts.

The above raise several questions regarding the relation between conceptual change learning and EF skills, such as the following: 1) Is inhibition the only EF skill recruited in the employment of science and mathematics concepts that require conceptual changes for their construction? 2) Is inhibition recruited in the employment of science and mathematics concepts in situations in which there is no need to reject a conflicting initial concept? In an attempt to start answering some of these questions we conducted a series of studies which compared the performance of elementary and high school students in two online conceptual understanding and change (CU&C) reaction time tasks and two Stroop-like EF tasks (Vosniadou et al., 2015, in press, submitted).

3.3. Studies in our lab

The CU&C tasks investigated conceptual change learning in 3 areas of science (physics, biology and chemistry and one area of mathematics (rational number). The Re-Categorization

task (Re-Cat) investigated individuals' ability to categorize a target concept (a word or a number) in initial or scientific categories. The Sentence-Picture Verification task (Sp-Ver) investigated individuals' abilities judge the truth or falsity of initial (common-sense) vs. scientific statements in relation to

a situation in the world (picture) to which they referred. The statements were either consistent with both initial and scientific views or inconsistent with one of them. Examples from the mathematics items of the two tasks can be found in figures 1 and 2.

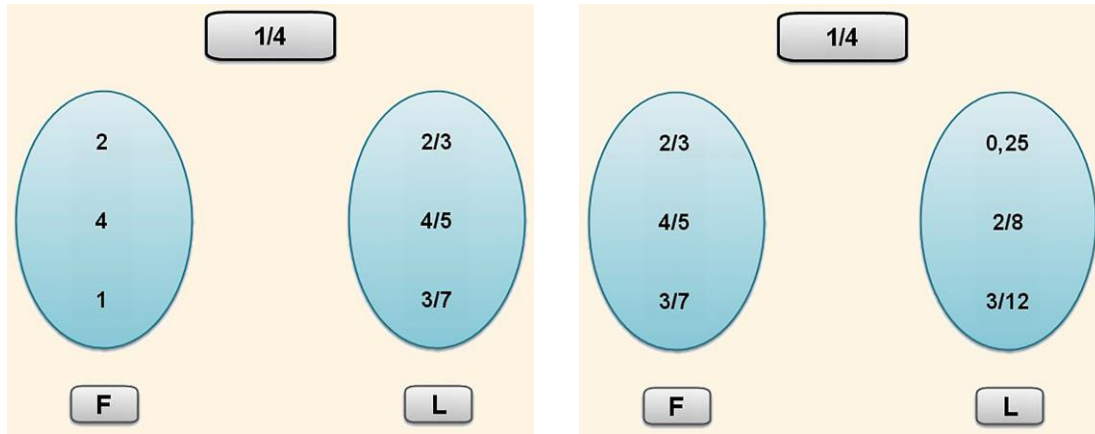


Figure 1. Examples from the mathematics items of Re-Cat task in the initial and scientific conditions

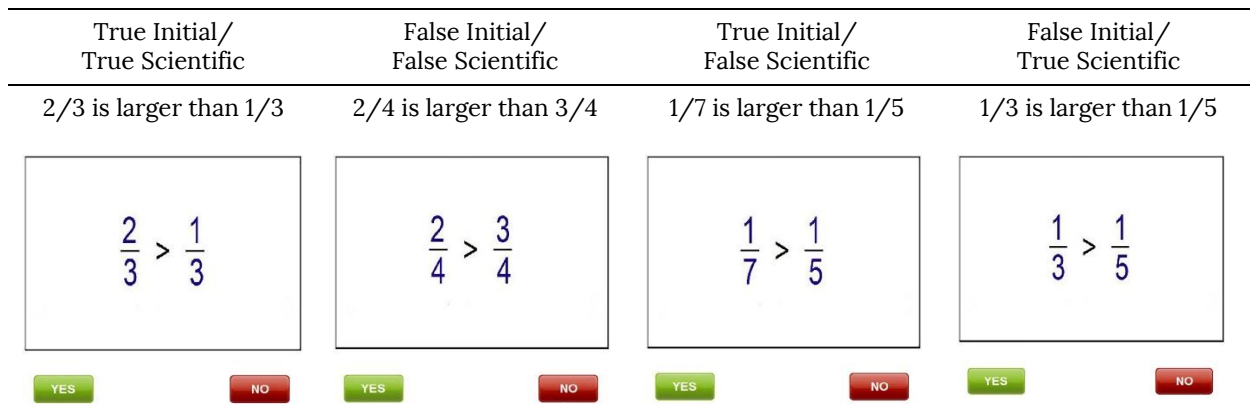


Figure 2. Examples from the mathematics items of the SP-Ver task in the two consistent and two inconsistent conditions

The Sp-Ver and Re-Cat tasks were validated by experts and by primary and secondary school students and were administered to 512 participants, ranging in age from elementary school students to university undergraduates (Vosniadou et al., submitted). CFAs on both accuracy and reaction times revealed that both tasks converged into two second-order factors – initial and scientific – and a common third order factor – conceptual understanding and conceptual change. The results also showed that the participants were less accurate and took more time to categorize the target concept in the scientific compared to the initial conditions of the Re-Cat and to verify the sentence/picture combinations in the consistent compared to the inconsistent conditions of the Sp-Ver.

The first study (Vosniadou et al., 2015) investigated whether performance in the two combined CU&C tasks would be predicted by the participants' performance in two EF tasks, which investigated inhibition and shifting in three modes (verbal, spatial, and numerical). Shifting was investigated because the tasks required the comparison of initial and scientific stimuli and we hypothesized that shifting might be recruited. The participants were 69 4th- and 6th-grade children. Only accuracy performance was investigated. A path model showed that accuracy performance in the combined scores of the incongruent conditions of the two EF tasks predicted accuracy performance in both the initial/consistent and the scientific/inconsistent trials of the combined CU&C tasks. Accuracy performance was also

predicted by intellectual ability measured by Raven's Progressive Matrices (Raven, Court, & Raven, 1985), while EF and the Raven were correlated with each other. A prediction analysis (Froman & Hubert, 1980) confirmed that the participants at the high and medium percentile of EF accuracy were much more likely to be high achievers in the conceptual change tasks compared to the participants in the low percentile of EF accuracy.

A subsequent study with 133 4th- and 6th-grade children investigated in greater detail the distinct roles of inhibition and shifting in the employment of scientific and mathematical concepts in the two conceptual change tasks separately (Vosniadou et al., in press). The two conceptual change tasks used in Vosniadou et al. (2015) were different in some important respects. The Sentence-Picture Verification task (hereafter Sp-Ver) was similar in kind to tasks used in previous research. As mentioned earlier, in this task the participants were asked to verify sentence-picture combinations in a consistent and an inconsistent condition. In the consistent condition, the scientific statements and the corresponding pictures were consistent with an initial, common-sense concept (they were both either true or false). In the inconsistent condition, the scientific statements and pictures were inconsistent with an initial concept (when one was true, the other was false). In the inconsistent condition the acceptance of the scientific statement required the participants to reject the initial, common-sense statement as false. Thus, in the Sp-Ver, the task demands differed between the experimental and control conditions. This was not, however, the case in the Re-Cat task.

The Re-Categorization task (hereafter Re-Cat) was different from the tasks used in previous research. In this task, the participants were presented with a target concept and were asked to decide to which of two categories it belonged best. In the initial condition, the participants had to decide between two categories that represented initial, common-sense, categorizations. In the scientific condition, they had to decide between two categories that represented an initial and a scientific categorization. Thus, in the Re-Cat the task demands were the same in the experimental and control conditions. In both cases, the participants had to compare the items that belonged to two different categories and decide which one is more similar to the target concept. In both cases, one of these two categories was better than the other and selection of one did not necessitate the falsification of the other. Both could be true.

The question of interest was whether the difference in task demands in the Re-Cat and Sp-Ver would influence the cognitive processes involved and therefore the EF skills employed. In the Sp-Ver task, accurate performance in the experimental but not in the control condition required the rejection of the initial concept as false. As such, we would expect the recruitment of inhibition in the experimental condition of this task only. In the Re-Cat task, the participants in both the experimental and control conditions had to compare the items in the two categories and decide to which category the target item belonged. While one category was

always better than the other (based on the 100 % agreement of experts) the selection of one category did not require the concomitant rejection of the other as false. As such, we would expect that shifting and maybe inhibition would be recruited in both the experimental and the control conditions in this task.

A regression analysis showed that inhibition was recruited only in the experimental condition of the Sp-Ver task, in which the rejection of the initial, common-sense statement was required. In this task inhibition accuracy predicted Sp-Ver accuracy. Shifting was recruited in all the tasks. Shifting accuracy predicted accuracy performance and RTs predicted RTs in both conditions of the Re-Cat task and in the consistent condition of the Sp-Ver task. Additionally, shifting RTs predicted accuracy performance in the experimental condition of the Sp-Ver task. In other words, the participants who were faster in shifting were significantly more likely to reject the initial, common-sense concepts in favor of the scientific ones. We interpreted this finding to mean that cognitive flexibility is important in this case because it gives more time to the executive system to inhibit the incorrect response (Vosniadou et al., in press). It should be mentioned here that the cognitive demands of the Sp-Ver task were significant and it is probable that working memory was also recruited. Future research will need to investigate the role of working memory in conceptual change tasks.

The above results were replicated in a third experiment with 203 7th- and 9th-grade students (Pnevmatikos et al., in preparation). The results again showed greater accuracy and slower RTs in the initial and consistent conditions than in the scientific and inconsistent conditions in the Re-Cat and Sp-Ver tasks respectively. However, a trade-off was also observed between accuracy and RTs. A significant condition by grade interaction showed that the participants increased their accuracy in the inconsistent condition of the Sp-Ver but not in the consistent condition. At the same time RTs became faster with age in the initial condition of the Re-Cat and the consistent condition of the Sp-Ver. For a more in-depth investigation of this trade-off, an efficiency performance score was constructed based on the accuracy/RT ratio (i.e., the proportion of the accurate responses to the time spent to complete each item). A series of regression analyses showed that inhibition was the predictor only for the inconsistent condition of the Sp-Ver task. Shifting was the predictor of efficiency performance in both conditions of the Re-Cat task and the consistent condition of the Sp-Ver.

To conclude and summarize, the results of the three experiments reviewed above showed that different cognitive processes were involved in the two tasks and that these processes recruited different EF skills. Inhibition was recruited specifically in the tasks in which the employment of the scientific concepts required the rejection of a contradictory initial concept as false. This result suggests that inhibition might be a more specialized EF skill that is recruited in certain kinds of conceptual change processes in which the rejection of initial, common-sense concepts or explanations is required. In these kinds of tasks, the speed of

shifting was also an important predictor of performance. Shifting was recruited in all the tasks in both the scientific and the initial conditions, suggesting that it is a more general EF skill important for tasks that require the making of comparisons, the detection of anomalies and the employment of different perspectives.

Future research needs to also investigate the recruitment of working memory in conceptual change tasks.

4. The role of EF in the construction of science and mathematics concepts that require conceptual changes

Carey and her colleagues (Carey, Zaitchik, & Bascandziev, 2015; Zaitchik, Iqbal, & Carey, 2013) have argued that the construction of concepts that require conceptual change is different from the construction of concepts which do not. Cases of conceptual change, they claim, require specific cognitive mechanisms to be accomplished, such as bootstrapping, i.e., a cognitive process that involves a kind of analogical reasoning, and these are the cognitive mechanisms that make heavy demands on EF skills. The argument for distinguishing the mechanisms that make conceptual change possible from the mechanisms that involve the accretion of facts is further strengthened by empirical evidence from studies of adults with Williams syndrome (a neurological disorder that causes mental retardation but allows for the development of language and factual knowledge). Adults with Williams syndrome fail to acquire a vitalist biology but develop normal factual biological understanding (Johnson & Carey, 1998). According to Carey et al., (2015; see also Zaitchik et al., 2013) the construction of vitalist biology in elementary school children constitutes an instance of conceptual change, over a previous agent-centered understanding of life by preschool children (see also Carey, 1985; Johnson & Carey, 1998; Carey et al., 2015). Young children identify life with movement and activity and thus attribute it only to animals and people (as well as to some inanimate objects that appear to be causal and intentional agents, like the Sun and the Moon) but not to plants. The construction of a vitalist biology requires considerable conceptual changes in preschool children's agent-based theory of life, including the differentiation of *alive* from *active* and *dead*, of *animate* from *inanimate* and the coalescence of *animal* and *plant* into the single ontological category of *living thing*. Zaitchick et al. (2014) hypothesized the reason why adults with Williams syndrome do not construct a vitalist biology is impairment in the mechanisms of EF and that these very EF mechanisms are necessary for the construction and expression of theoretical knowledge.

Is there any behavioral evidence for the recruitment of EF skills in the construction of science and mathematics concepts that require conceptual change? Zaitchik et al., (2013) investigated the hypothesis that individual differences in EF skills can explain, at least partly, the construction of a vitalist biology in young children. Their participants were 79 children, ranging in age from 5 to 7 years. The results showed

that the children's scores in a battery of EF tasks significantly predicted their vitalist biology knowledge, even after controlling for age and verbal IQ. Although this study confirmed that there is a relation between EF skills and vitalistic biology, it was inconclusive as to whether the EF skills tested were recruited in the construction of biological knowledge or in the demonstration or employment of this biological knowledge after it had been constructed. Furthermore, the EF tasks (Hearts & Flowers, Flanker Fish, and Color Words) and measures used (a combined measure of accuracy in some of the conditions and failures to respond to stimulus) were not exact enough to draw inferences as to which specific EF skill might have been involved.

Laski and Dulaney (2015) in the paper discussed earlier which investigated the employment of linear vs. logarithmic numerical investigations, also investigated the hypothesis that individual differences in inhibitory control are related to the rate to which children benefit from instruction relevant to number estimation. They hypothesized that the children with better inhibitory control are better at inhibiting their bias towards the logarithmic representation more readily in order to construct a linear representation. Their results showed that individual differences in inhibitory control did predict the rate at which playing a numerical board game improved number line estimates in children. The children with above average inhibitory control demonstrated rapid improvement in the linearity of their number line estimates as opposed to children with below average inhibitory control who demonstrated no improvement. This relation between inhibitory control and learning existed after controlling for pretest estimation performance.

Although this study is correlational in nature, it suggests that inhibitory control is recruited in the construction of linear representations of numerical magnitude in off-line tasks. A limitation of the study is that it did not control for the influence of other EF skills such as shifting and working memory, and other factors such as IQ. More importantly, it did not test whether there are causal relations between inhibition and numerical line estimation.

5. Implications for Education

Our studies of conceptual change in science and mathematics (see Vosniadou & Skopeliti, 2013) show that it might not be necessary to posit qualitatively different cognitive mechanisms to account for the construction or employment of science and mathematics concepts that require conceptual changes. Considerable knowledge revision can be achieved by relying on the use of constructive, additive cognitive mechanisms. However, it is possible that the cognitive mechanisms that produce knowledge revision place heavier quantitative demands on the efficient use of EF skills and specifically of inhibitory control. While inhibition might be used in many other instances of learning, it seems to carry important weight in the kind of learning that requires the suppression of what is known in order to learn something new.

This hypothesis is supported by research indicating that conceptual change learning does not usually take place through radical, Gestalt type knowledge restructurings but is a slow and gradual affair. It appears that one way children might eventually produce conceptual change learning is by constructing new beliefs and new mental representations gradually by adding the new, incompatible scientific information to what they already know, often producing misconceptions. This gradual, constructive learning process does nevertheless require that some prior beliefs are rejected as false or are accepted as belonging to a different explanatory framework. Such evidence can be found, for example, in Wiser and Smith's (2008) description of the development of children's understanding of matter, Vosniadou and Brewer's (1992, 1994) description of the development of children's representations of the shape of the Earth and of the day/night cycle, Evans' (2008) description of developmental changes in children's biological explanations as well as in Shtulman's (2006) account of the subtle differences in adults' understanding of evolution.

The research reviewed in this paper shows that EF skills such as inhibition and shifting are recruited in conceptual change tasks and that inhibition seems to play a unique role in the cases in which scientific information is inconsistent with initial concepts and requires their rejection as false. However, causal relations have not been established. In order to do so, studies are required which will provide training in inhibition and/or other EF skills and then examine whether subsequent improvements in the EF skills provided have an effect on the construction and employment of science and mathematics concepts in conceptual change tasks.

Existing research has shown that although inhibitory control and other EF skills can be improved through training (Diamond, 2012), the effects of this type of training are limited and do not often transfer even to different, non-trained, inhibition tasks (Kray & Ferdinand, 2013). On the other hand, there is also evidence that the learning environment can influence the development of EF skills (see Zelazo, Blair, & Willoughby, 2016). Thus, there might be a bi-directional causal relation between EF skills and the learning of counter-intuitive science and math concepts, such as that improvement in one can have positive effects on the other. Reviews of the effectiveness of training studies agree in general with the recommendation that more generalized benefits are likely to result when EF training is embedded within the curriculum (Diamond & Lee, 2011; Holmes & Gathercole, 2013). Future research needs to carefully investigate the effects of different kinds of EF training on the construction and employment of science and mathematics concepts that require conceptual changes. This might open a new path of effective interventions in school settings aiming at the early integration of executive function training with the teaching of science and mathematics in order to improve students' learning and academic achievement.

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