The Neuroscience of Conceptual Learning in Science and Mathematics

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Abstract

Learning new concepts in mathematics and science often involves inhibiting prior beliefs or direct perceptual information. Recent neuroimaging work suggests that experts simply get better at inhibiting these pre-potent responses rather than replacing prior concepts with the newer concepts. A review of both behavioral and neuroimaging evidence with children suggests that improving inhibitory control is a key factor in learning new scientific and mathematical facts. This finding has implications for how these subjects are taught in the classroom and provides corroborating evidence for practices already in place.

Introduction

What sets us aside from most other species is our ability to develop abstract and causally-based concepts[1]. These concepts go beyond the information immediately available through direct perception and encode an understanding of how elements in the world relate to one another in general. Acquiring such abstract concepts underpins school-based learning in both mathematics[2] and science[3, 4]. However, any pupil aiming to acquire "new" concepts in science and mathematics needs to overcome the strong pull of existing beliefs that have served them so well until then. In science education, this so-called "conceptual change" is a formidable obstacle in acquiring knowledge that goes beyond popular belief or perception[5]. Similarly, in mathematics, the child needs to go beyond the perceptually obvious solutions to understand and apply formal logical solutions to a problem[6, 7, 8].

Recent work in scientific reasoning has suggested that the inhibition of pre-exiting beliefs through the activation of the dorsal lateral prefrontal cortex (DLPFC) and the anterior cingulate cortex (ACC) is an integral part of the successful evaluation of counterintuitive science and mathematics evidence[9, 10]. Thus, in this article, we will review the role that concepts play in mathematics and science learning and explore how the brain controls the many competing beliefs that we hold in mind at any one time, in a way that allows us to take on new ideas.

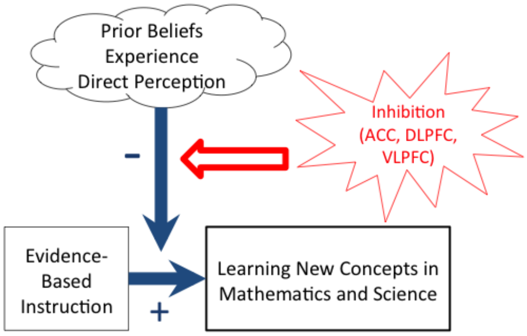

Figure 1. Learning counterintuitive concepts in mathematics and sciences involve increasingly proficient levels of selective inhibition of prior beliefs, and information acquired through direct experience and direct perception with age and experience. Acronymes: ACC: anterior cingulate cortex, DLPFC: dorsolateral prefrontal cortex, VLPFC: ventrolateral prefrontal cortex.

Conceptual change in Science and Mathematics

Scientific reasoning involves the evaluation of newly gathered evidence and the integration of this evidence into one's existing concepts, theories or models of the physical and biological world. Contrary evidence may require the revision of existing theories[4, 11, 12], or the development of an entirely new theory, a process called *conceptual change*[5, 13]. A key element of learning any new concepts is the need to overcome strongly held prior beliefs about a domain before new knowledge can be effectively assimilated[14, 15]. Thus, a major challenge in mathematics and science education is the need for children to inhibit pre-existing beliefs or superficial perception in order to engage in acquiring and applying new and counterintuitive knowledge[13, 16, 17, 18]. Because of the importance of this process in scientific reasoning, many researchers have focused on investigating the naïve concept*s* that children and adults hold about phenomena in various scientific domains. In this approach, the goal is often to describe and uncover the mechanisms underlying conceptual change as a function of new learning[13. 20, 21] in, for example, domains such as biology[22], physics[23,] or evolution[24].

But what happens as we become experts? Are old concepts overwritten, simply forgotten, or do they continue to impact on our thinking. Brain imaging data from adults (typically university students) are especially informative here. In a range of tasks it has been shown that the interplay between the anterior cingulate cortex (ACC), which supports conflict detection, and multiple regions of the prefrontal cortex supporting attention, inhibitory control, working memory and the integration of information, plays a critical role in the detection of, and subsequent modification of beliefs and scientific understanding in response to conflict between new and prior knowledge[10, 25, 26]. These results suggest that an important part of the neural basis of scientific and mathematical learning lies in the detection of an anomaly, the inhibition of prior beliefs, and the integration of new information and concepts into an updated scientific understanding.

Conceptual knowledge in the brain

Brain imaging studies have made a real contribution to our understanding of how conceptual knowledge is represented[27]. Two general distinctions are identified: (1) a spatial one, whereby "perceptual" processing is associated with more posterior activity, over the areas involved in the first steps of visual analysis, while more abstract processing is associated with frontal and temporal activity, and (2) a temporal one, whereby "perceptual" processing precedes more abstract "conceptual" analysis.

That said, "conceptual" knowledge is located in broad distributed networks[28] involving many parts of the brain, including: (1) overlapping but partly distinct neural systems for processing concrete and abstract concepts, with greater involvement of bilateral association areas during concrete word processing, and processing of abstract concepts almost exclusively by the left hemisphere[29], (2) amodal representations that transcend particular input modalities[30, 31], and (3) embodied knowledge which is embedded within specific sensori-motor systems[32]. Access to this conceptual knowledge therefore requires executive control to leverage those parts of the network that are helpful for the current task and suppress the rest[33, 34, 35].

Close collaboration between the various knowledge representation networks and a cognitive control network is therefore essential for the effective management of existing knowledge and the acquisition of new knowledge[36]. Given the complex interrelated networks involved in representing conceptual knowledge, a key challenge is to overcome interference and inhibit irrelevant information while activating the relevant information. Standard information processing approaches to cognition (that abstract away from neural processes) represent processes as encapsulated modules (e.g., attention module, working memory module, etc.). However, the control of knowledge within neural networks is embedded within particular domains of knowledge[33, 37]. This suggests that training executive control skills (such as general working memory capacity or inhibitory controls) without embedding the training within a specific knowledge domains may not have as much impact on the control of knowledge as training within a target domain. Indeed, a recent review of the effectiveness of executive functioning training[38] finds that there is little evidence of transfer from training on abstract executive function tasks to academic skills, although embedding such activities within the classroom appears to be much more effective[39].

Inhibition and the control of conceptual knowledge

The development of inhibition and the control of interference has long been established as a central limiting factor in cognitive development[7, 40]. Children have the capacity to make inhibitory responses from infancy, but only gradually get better at using this ability[41]. During interference control, children show more diffuse frontal cortex activations and a greater recruitment of posterior brain regions; adults by contrast show more focal activation in the DLPFC, ACC and inferior frontal gyrus[42, 43]. Similarly, neuroimaging evidence with children shows a shift from posterior perceptual processing regions to fronto-parietal activations correlating with age and improved performance on logic and mathematical problems[44, 45]. This has been interpreted as showing that children need to inhibit initial perceptually bound beliefs before being able to successfully apply the more abstract and (frontally dependent) reasoning skills required in math and logic. Convincing evidence of this shift was presented in a recent meta-analysis of functional magnetic resonance imaging (fMRI) data obtained over a decade (1999–2008) on more than 800 children and adolescents engaged in numerical tasks. This analysis revealed that, unlike adults, children primarily engage the frontal cortex when solving numerical tasks. This is consistent with the argument that, with increasing age, there is a shift from a reliance on the frontal cortex to reliance on the parietal cortex in mathematical reasoning tasks[46], perhaps due to reduced cognitive load as children gradually acquire expertise in mathematics. Though it should be noted that this conclusion relies on the reference inference that because frontal regions are more active, greater inhibitory control is being exerted. Given the prolonged development of the frontal lobes[43] it is not possible to be entirely sure that functions observed in the developing brain are identical to those observed in the mature adult brain, even if the activation patterns are similar.

A second strand of evidence comes from Evans[47] who posited that there are two competing cognitive systems underlying reasoning: the heuristic system, which is evolutionarily old, fast operating, automatic and parallel; and the analytic system, which is slow operating, rule based, sequential in nature, and although limited by working memory capacity, underlies abstract logical reasoning and hypothetical thinking. A defining property of the dual process model of reasoning is that the analytic system is able to inhibit and override the heuristic system so that individuals can successfully carry out logical tasks[48, 49, 50]. Neuroimaging work on logical and scientific reasoning in adults has consistently shown that the inhibition of pre-existing beliefs, misleading perceptual-biases, and intuitive heuristics is associated with the activation of the anterior cingulate cortex (ACC) and the prefrontal cortex, notably the inferior frontal cortex (IFG) and dorsolateral prefrontal cortex (DLPFC)[10, 11, 25, 26, 48]. Critically, Houdé et al.[45] provided neuroimaging evidence of a switch, after a brief training in logical reasoning, from the heuristic system to the analytic system in adults.

To explore this idea further, several labs[25, 26] have used an fMRI protocol to obtain functional brain images of novices and experts while performing a cognitive task in mechanics, a scientific discipline for which misconceptions are known to be frequent and persistent. They found that experts, significantly more than novices, activate brain areas associated with inhibition; specifically, the right ventrolateral prefrontal cortex and the left dorsolateral prefrontal cortex. This suggested that the experts' misconceptions in mechanics had not been eradicated or transformed during learning but rather that they had remained encoded in their brains and were then inhibited to provide a correct answer.

Evidence from the classroom

Is there any behavioral evidence (relevant to educational practitioners) of the importance of inhibitory skills in mathematics and science learning? Gilmore, et al.[51] have recently explored how inhibition skills are related to overall mathematical achievement as well as factual, procedural and conceptual knowledge in 209 participants aged 11 to 12 years, 13 to14 years, and adults. These authors found that general mathematics achievement was more strongly related to inhibition measured in numerical compared with non-numerical contexts. Inhibition skills were related to conceptual knowledge in older participants, but procedural skills in younger participants. There is also some evidence[52] of a contribution of hippocampal–prefrontal circuits (specifically DLPFC and VLPFC) related to the early development of retrieval fluency in arithmetic problem solving. Finally, recent research suggests that executive function skills, such as suppressing distracting information and unwanted responses (inhibition) play a critical role in the development of mathematics proficiency[53, 54].

The continued development of prefrontal lobes during early adolescence[41, 43] would imply an improvement with age in students' abilities to inhibit task-irrelevant information and coordinate task-relevant information, thereby enhancing their scientific reasoning abilities as well as their ability to reject scientific misconceptions and accept scientific conceptions, well into adolescence. To test this hypothesis, two hundred and ten 13 to 16 year old Korean secondary school pupils were tested with 4 tasks known to load on pro-frontal activity, a test of scientific reasoning ability, and a test of air pressure concepts derived from kinetic- molecular theory[55]. The measures of prefrontal lobe activity correlated highly with scientific reasoning ability. In turn, prefrontal lobe activity and scientific reasoning ability predicted concept gains and posttest performance. A subsequent principal components analysis showed that the study variables had two main components, which were interpreted as an inhibiting and a representing component. The authors interpreted this as evidence for both the inhibition of task-irrelevant information (i.e., the rejection of intuitively derived misconceptions) and the representation of task-relevant information (i.e., complex hypothetico-deductive arguments and counterintuitive scientific conceptions about non-observable entities).

Conclusion

Imaging and behavioral methods from the developmental cognitive neurosciences have enabled us to make great strides in understanding what underlies the complex neural and cognitive processes involved in mathematical and scientific concept learning. In turn, this work should suggest classroom-based interventions that will improve both science and mathematics educational outcomes[53]. A few interventions have begun to implement cognitive control training within the classroom environment or within mathematics and science teaching [16, 56, 57, 58]. Results show long-term effects and more generalizable benefits when the training is embedded within the curriculum than when it is not[16, 39].

Finally, it is reassuring to note that the recent emphasis on the importance of inhibitory control in learning science and mathematics, which emerges from the cognitive neuroscience research, is entirely consistent with older practice-based recommendations to encourage students to take a moment of “waiting time” before responding during science lessons[59]. By combining these practice-based discoveries with the emerging neural-based evidence, we can be increasingly confident of our success in improving conceptual learning in mathematics and science education. While there is already a sense among teachers that inhibitory control is a foundational skill in mathematics learning[60], feeding back the cognitive neuroscience evidence can only strengthen this conviction and further improve practice.

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Figure 1: