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Using fMRI to study conceptual change: Why and how?

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Although the use of brain imaging techniques, such as functional magnetic resonance imaging (fMRI) is increasingly common in educational research, only a few studies regarding science learning have so far taken advantage of this technology. This paper aims to facilitate the design and implementation of brain imaging studies relating to science learning by presenting the epistemological and methodological framework of an ongoing fMRI study trying to identify brain mechanisms related to conceptual change in electrical concepts. To achieve this goal, we propose a review of literature, in the first part of this paper, to explain why we choose to study conceptual change using fMRI. In the second part, we present the methodology of an ongoing study to show how brain imaging can be applied in science education research.

Keywords: brain imaging, conceptual change, educational neuroscience, neuroeducation, science education

Introduction

In recent years, a growing number of educational researchers (Fischer et al. 2007; Geake, 2003, 2004; Geake & Cooper, 2003; Goswami, 2004, 2006) and cognitive neuroscience researchers (Houdé, 2006; O'Boyle & Gill, 1998; Petitto & Dunbar, 2004) have shown an interest in the development of a neuroscientific approach to study educational problems. The interest for this new approach, supported notably by the OCDE (2007) and the Royal Society (2011), is explained partly by recent findings relating to the brain, which are of particular interest to the field of education. These findings relate to, among others, the learning of reading (Beaulieu et al. 2005; Yoncheva et al., 2010) and mathematics (Grabner et al., 2007, 2009).

Although neuroscience research related to education is becoming increasingly encouraged and widespread, there is only a limited number of studies on brain mechanisms related to the learning and teaching of science (Dunbar, Fugelsang, & Stein, 2007; Fugelsang & Dunbar, 2005; Nelson, Lizcano, Atkins, & Dunbar, 2007; Petitto & Dunbar, 2004). In fact, since the advent of functional magnetic resonance imaging (fMRI) during the 1990s (Kwong et al. 1992; Ogawa et al., 1990, 1992), over one hundred studies on learning of reading (Dehaene, 2007) and mathematics (Ansari, 2008) have been undertaken, but fewer than a dozen are specifically about science learning. There are probably several reasons to explain this situation, but it is likely that one of them is caused by the difficulties encountered by researchers in adapting brain imaging methodologies to the field of science education.

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The aim of this paper is to facilitate the design and implementation of brain imaging studies relating to science learning by presenting the epistemological and methodological framework of an ongoing fMRI study trying to identify brain mechanisms related to conceptual change in electrical concepts. The discussion is structured around two questions: (1) why is it interesting to use brain imaging to study science learning and (2) how can it be used? To answer the first question, we propose a review of the literature to discuss the benefits of using fMRI to study science learning and, to answer the second, we present the methodology of an ongoing study to show how brain imaging can be applied in science education research, which leads us to discuss the issues relating to the use of this type of technology (subject selection, task design, data analysis, etc.).

Why use brain imaging to study conceptual change?

Our choice to use brain imaging to study conceptual change is based primarily on two arguments. The first is that brain imaging allows the study of conceptual change at an unexplored level of analysis that can both stimulate new research hypotheses and test those already existing. The second argument is that there are already existing a few neuroscientific studies on conceptual change, which are not only interesting, but are opening the way for a totally new vision of conceptual change processes based on the concept of inhibition. The next two subsections discuss these arguments.

Brain imaging provides research data to an unexplored level of analysis

The science learning is perceived by students (and often by teachers) as a difficult and demanding process. Usually, this difficulty is attributed to the fact that science is based on abstract concepts (diSessa, 2006) that require the use of complex mathematical tools. In the late 1970s and early 1980s, researchers in science education (e.g. McCloskey, 1983; Viennot, 1979) proposed a new hypothesis concerning the root causes of the difficulties encountered by students when they learn science concepts. According to these researchers, learning science is difficult not simply because it is based on an abstract process involving specific mathematical skills, but because students and people in general believe, before and even after their first science course, in their spontaneous conceptions that are in conflict with accepted scientific knowledge and that interfere with the learning of science.

The importance of such misconceptions for students in science learning is currently supported by a large volume of research, including excellent literature reviews (Confrey, 1990; Legendre, 2002; Wandersee, Mintzes, & Novak 1994), substantial directories of dozens of common misconceptions in most scientific domains (Thouin, 1996), and bibliographies containing references on thousands of research articles on students' conceptions (Duit, 2009). In fact, students' misconceptions have been, during the last few decades, the object of an unprecedented research effort in the recent history of research about science learning. This effort is justified not only because these misconceptions are frequent, but also because they are particularly difficult to eradicate, which makes the persistence of these misconceptions a fundamental obstacle to science learning. This persistence is so strong that the misconceptions can last even after several years of learning science. For example, despite having studied electricity for many years, over 10% of second-year engineering undergraduates continue to believe that a single wire is required for a bulb to light (Periago & Bohigas, 2005). This situation is not unique to the learning of concepts related to electricity, since over 25% of first-year physics undergraduates continue to believe that a metal ball the same size as a plastic ball will reach the ground faster when dropped (Wandersee et al., 1994).

In parallel with studies on the identification of students' conceptions, researchers have attempted to understand the processes that an individual must go through to achieve a conceptual change, i.e. a successful transition from a misconception to a more scientific understanding of concepts. One of the first models of conceptual change - and one of the most cited in research literature in the field – was proposed by Posner, Strike, Hewson and Gertzog (1982). This model, inspired by Piaget (1967) and Kuhn (1962), suggests that the passage from an inadequate understanding to a more appropriate one depends on several conditions: (1) there must be dissatisfaction with existing conceptions, (2) the new conception must be intelligible, (3) it must be credible and (4) it must be fertile, i.e. allowing the discovery of new solutions to new problems.

Despite being the most cited, the model of Posner et al. (1982) is far from being unanimously accepted. In fact, various researchers propose different models of conceptual change. For example, the model of Duit and Treagust (2003) proposes that students' conceptions are located within a larger conceptual structure. Thus, what must evolve during conceptual change is not only an individual's conception, but also all the conceptual structure that underlies and supports it. For Vosniadou (1994), it is important to situate the notion of conceptual change above the conceptual level, because conceptions, conceptual frameworks and concepts are, according to her, incorporated into a larger theoretical framework. Forming a "naive theoretical framework", these large structures do not consist of concepts - as is the case for the notion of conceptual structure by Duit and Treagust (2003) - but of ontological and epistemological presuppositions developed during childhood. Unlike Vosniadou, diSessa (1993) believes, however, that the responses made by non-science students are not necessarily based on naive theories, but originate rather from improper use of intuitive and sub-conceptual cognitive tools called phenomenological primitives (p-prims). During the processes of conceptual change, the use of a p-prim or a set of p-prims by learners evolves, according to diSessa (1998), because the student gradually develops a coordination class, i.e. a complex systems of knowledge with several parts including p-prims (diSessa, 2006). This view postulates that conceptual change is a process by which an individual moves from an intuitive use of p-prims to a more systematic one that is supported by all the organized elements of a coordination class. To summarize, for diSessa, conceptual change is a process by which an individual develops a coordination class in agreement with scientific knowledge. It should be noted that many other models of conceptual change exist, including those of Chi (1992), Pintrich (1993) and Stavy and Tirosh (2000). The large number of models proposed, along with the large volume of articles on conceptual change, shows the importance of conceptual change, but also the extent of research that remains to be done.

Although some models of conceptual change are likely to be mutually beneficial, it often appears, as explained in the previous paragraph, that the models proposed by different researchers are based on fundamentally opposed assumptions. The existence of this variety of hypothetical and often contradictory models demonstrates the complexity of mental processes involved in conceptual change and explains why, despite the efforts of researchers, the fundamental processes associated with conceptual change are still poorly understood. Andrea A. diSessa (2006, p. 266) summarizes the current situation in an article on the history of research on conceptual change: "There are, in fact, no widely accepted, well-articulated, and tested theories of conceptual change. Instead, the field consists of multiple perspectives that combine many commonsense and theoretical ideas in kaleidoscopic fashion." Thus, in order to significantly improve current knowledge in the field of conceptual change, it seems essential to further develop the basis of empirical knowledge in this field.

One of the most promising and original ways to contribute to the development of the database of empirical research is to use recently developed brain imaging techniques. Used for the first time in the early 1990s in psychology (Ogawa et al., 1992; Kwong et al., 1992), fMRI allows measurement of different brain regions' activity during a cognitive task, such as reading, counting and even solving scientific problems (Masson, 2007). Since our knowledge of the cognitive role of brain regions is continuously increasing through cognitive neuroscience (Gazzaniga, 2004; Houdé, Mazoyer, & Tzourio-Mazoyer, 2001), it is possible to better understand the nature of cognitive resources that must be mobilized when solving scientific problems. In fact, it has recently become possible to analyze the processes of conceptual change in the brain by studying changes in brain activity linked to the achievement of a conceptual change (Dunbar et al., 2007; Nelson et al., 2007). These neuroimaging studies on conceptual change are particularly interesting because they provide information about a variable that has not been measured yet: brain activity. The information provided by this new variable, combined with information coming from other types of research, may, in our opinion, contribute to a better understanding of the nature of conceptual change.

Brain imaging allows to study certain educational problems (including those related to conceptual change) at a level of analysis unexplored, i.e. the brain (Geake & Cooper, 2003; Dunbar et al., 2007). Accessing this new level of analysis may entail important benefits for research. For example, since brain imaging provides information about the constraints imposed by the brain on cognitive processes, it could stimulate the formulation of new hypotheses about the nature of the cognitive processes involved in academic tasks, and it might help researchers to choose among different and competing cognitive models. Moreover, according to Goswami (2004), brain imaging allows us to know the effect of an educational intervention on the brain, in addition to helping to diagnose children with learning difficulties.

Recent discoveries using brain imaging techniques lead to new interpretations on the nature of conceptual change

The theoretical and methodological framework of our ongoing research related to conceptual change in electricity is mainly based on three studies. In the first, Fugelsang and Dunbar (2005) investigated, using fMRI, what happens in the brain of subjects when they see information (or data) in opposition or in agreement with their conceptions regarding the effectiveness of a medication against depression. The presentation of information that contradicts the subjects' conception places them in a cognitive conflict situation, equivalent to the one that would induce unexpected data in an academic context of scientific experimentation. The information is presented in the form of images showing a pill next to a man who is smiling (effective medication) or depressed (ineffective medication). These images are presented one after another in blocks containing smiling (or not) faces, which provides data that globally agree or disagree with the conceptions of participants. Having reviewed the information blocks, participants must evaluate the effectiveness of the medication on a scale from 1 (low) to 3 (high).

Researchers found that the hippocampus, a brain region associated with learning and memory (e.g. Poldrack et al., 2002), is more activated during the presentation of information in agreement with participants' conceptions than during the presentation of information in disagreement. This could mean that individuals integrate information more effectively when it is in accordance with their conceptions. They also found that the anterior cingulate cortex associated with conflict detection (Botvinick, 2007), the left dorsolateral prefrontal cortex related to inhibition (Goel & Dolan, 2003) and the precuneus associated with the reallocation of the attention (Mazoyer, Wicker, & Fonlupt, 2002) are more activated during the presentation of information that is in opposition with the individuals' conceptions than during the presentation of information that correspond to them.

According to the authors of this study, these findings suggest that the brain first detects, with the help of the anterior cingulate cortex, the existence of a conflict between their conception of the drug's effectiveness and the data presented. Then, instead of activating brain areas associated with learning like the hippocampus, the brain, using the dorsolateral prefrontal cortex, stops the attention required by the task, as if the data were irrelevant since they were erroneous. Finally, the brain activates the precuneus to divert attention from the task. According to Dunbar et al. (2007), this clearly shows that a teaching strategy based solely on cognitive conflict, i.e. the presentation of data incompatible with the individuals' conceptions, may not produce conceptual change, since participants in the study seem to treat information received as if it was erroneous and uninteresting, rather than interesting and potentially conducive to learning.

In the second study, Dunbar and his colleagues (Dunbar et al. 2007; Petitto & Dunbar, 2004) explored brain mechanisms underlying the process of conceptual change in the learning of mechanical physics. To do so, they compared the brain activity of two groups: a first group constituted of university students who had not taken any advanced scientific courses and a second constituted of university students who had completed at least five advanced courses in physics. Students of both groups had a comparable average academic level and comprised equal numbers of men and women. The cognitive task required participants to press a button to indicate if the movie showing two falling balls was consistent with what would happen in a frictionless environment. Participants were presented with naive movies (i.e. consistent with novices' conceptions: the biggest ball falls faster) and scientific movies (i.e. in line with experts' conceptions: the biggest ball falls at the same speed as the smaller).

One of the most interesting results of this study is that the novice students who gave scientifically correct answers showed a notable activation of their anterior cingulate cortex (associated with conflict detection), despite the fact that participants claimed that they did not perceive conflicts between their views and information presented. According to Dunbar et al. (2007), this could mean that novices have not made a profound conceptual change, but instead have learned to inhibit inappropriate responses. This idea of inhibition is particularly interesting, because it challenges researchers' typical representation of the nature of conceptual change, which often consists of eradicating or radically restructuring prior knowledge.

As stated by Dunbar et al. (2007), several educational theorists see conceptual reorganization as the main purpose of science education, and consider that conceptual change prevents students from any longer being able to conceptualize their old theories after such a change (Kuhn's notion of incommensurability). However, the results of this experience suggest that, even when students appear to have achieved conceptual change, it seems that they still have access to their old misconceptions, and that these misconceptions are actively inhibited by experts in science rather than reorganized and absorbed into a new theory.

In a third study, this time on brain mechanisms related to conceptual change in chemistry (more specifically, on phase changes of matter), Nelson et al. (2007) asked novices (who had taken no science courses other than general chemistry in high school and had not studied such chemistry courses for at least two years) and experts (who had taken at least four chemistry courses) to indicate whether a picture shows correctly or incorrectly what happens to molecules and atoms of a liquid after evaporation. As in the study about mechanics, the task was composed of scientific and naive stimuli.

These researchers found that experts showed more activation in their prefrontal cortex, whereas novices showed more activation in their inferior temporal lobe and occipital lobe. At least two interpretations of these results seem plausible. In the first (supported by the authors of the study), these results support the idea that novices rely more on visual and attention-related mechanisms, while experts' cognitive work relies more on brain regions linked to working memory and to semantic retrieval (i.e. the memory retrieval of knowledge in chemistry).

It seems important to us to not yet dismiss the second interpretation, in which the differences recorded between experts and novices can be explained by the concept of inhibition. Under this alternative interpretation, novices, like experts, tend naturally to use a perceptual strategy that consists of imagining the molecules and atoms diverging from one other during evaporation (hence the activation of the lower temporal lobe and occipital lobe by the novices). Unlike novices, however, experts are able to inhibit the neural networks associated with the spontaneous strategy, leading to erroneous answers, by involving the prefrontal cortex areas that can be associated not only with working memory and semantic retrieval, but also with inhibition. The main objection to this second interpretation, however, is that the anterior cingulate cortex, usually activated in research on inhibition, does not seem to be significantly more activated by experts in the study of Nelson et al. (2007). However, since it is possible that the cingulate cortex is indeed more activated in experts, but just not enough to make a statistically significant difference, we believe that one should not reject this alternative interpretation.

These three studies have considerable implications for research on conceptual change. The first one questions the effectiveness of the use of instructional strategies based only on cognitive conflict. The second challenges the fundamental idea that conceptual change implies a major restructuring or elimination of prior knowledge, and proposes to include the concept of inhibition in our understanding of conceptual change processes. Finally, the third one provides the first elements of a neuroscientific model of conceptual change, which would explain how prior knowledge might be inhibited with better cognitive control. Without the use of brain imaging, none of these discoveries would have emerged; thus we believe that these results, together with further research about the role of inhibition in conceptual change, will have significant impact on science learning and teaching in the coming years.

How to use brain imaging to study conceptual change?

After discussing the advantages of the use of brain imaging to study conceptual change, we present in this second section how we use fMRI in our ongoing study of brain mechanisms that underlie conceptual change in electricity. As you will see, we borrow many methodological strategies from the three studies discussed in the previous section: we select a common misconception hard to change (only one wire is sufficient to light a bulb), we develop a cognitive task related to that misconception and we compare brain activity of novices (who have not achieved a conceptual change) and experts (who have achieved it).

Defining operational research hypotheses

In a neuroimaging project, research hypotheses play a central role. They must both be built on existing knowledge about the functioning of the brain and be sufficiently operational to enable satisfactory data interpretation. In general, a hypothesis will take the form: "If the independent variable X increases (or decreases), then the activity of brain region Y should increase (or decrease)." (Huettel, Song, & McCarthy, 2004).

The hypotheses of our research regarding conceptual change in electricity are based on evidence from studies discussed in the previous section. First, in both the study of Fugelsang and Dunbar (2005) and of Dunbar et al. (2007), the anterior cingulate cortex, a region that Botnivick (2007) associated with conflict detection, is more activated when the information presented is in conflict with the initial conceptions of the participants. Second, in the study of Nelson et al. (2007), we observed that novices in chemistry use more brain regions associated with perceptual strategies, while experts experience greater activation of high-level cognitive functions located in the frontal lobe. Botvinick's theory links these two experimental results: the activation of the anterior cingulate cortex detects conflicts that signal the need to use high-level cognitive control functions located in the prefrontal cortex and one of the most important cognitive control functions is inhibition.

Based on these studies, we believe that to achieve conceptual change, the individual must learn to inhibit inappropriate responses based on misconceptions by using more brain regions related with conflict detection (anterior cingulate cortex) and cognitive control (regions of the prefrontal cortex). The central hypothesis of our study is thus proposed: experts in science activate more their anterior cingulate cortex and their prefrontal cortex than novices.

Choosing a sample of subjects that is sufficiently homogenous and of adequate size

To detect statistically significant differences between different conditions or between individuals of different population, it is necessary to have a sufficient number of subjects per group, and to ensure that the brain variability between subjects within a group is as small as possible. To reduce this variability, it is necessary to determine selection criteria favoring the production of a relatively homogeneous sample. To reduce the variability caused by differences due to gender (Grabner et al., 2007), age and handedness, the participants forming the two groups in our study (experts and novices) are right-handed men, aged from 19 to 30. Likewise, to control for the possible effects of educational level, participants in both groups are bachelor's degree students, and students with an atypical academic score (less than 2.3 on 4.3 or higher than 4.1 on 4.3) are excluded from the study.

Our two subject groups are respectively composed of 12 novices and 11 experts in science. The selected novice participants are undergraduate students in humanities subjects, who have never taken an optional science course during their education. In addition, their answers to a questionnaire show that they believe in the misconception that only one wire is sufficient to light a bulb with a battery (which is scientifically incorrect) and that they believe that a light bulb does not light up if the wire connecting the battery to the bulb is broken (which is scientifically correct). During the fMRI session, selected participants are required to answer (1) whether it is incorrect that a bulb connected to a battery by a single wire lights up, (2) whether it is incorrect that a bulb connected to a battery by a single wire does not light up (3) whether it is correct that the bulb turns off if the wire connecting it to a battery is broken. The subjects that do not answer as described above to 90% of the questions asked are excluded from the study.

The expert participants are undergraduate students in physics whose questionnaire responses indicate they do not believe that a single wire is sufficient to light a bulb, thereby supporting the idea that they have made a conceptual change during their scientific training. As for novices, experts are also expected, in the questionnaire, to assert that a bulb will not light if the wire connecting it to the battery is broken. Again, like for novices, expert participants failing to answer correctly as expected to 90% of the questions asked are excluded.

Educational researchers may find it surprising that the number of subjects in this study is this small, but it is in fact not uncommon to find such a small sample size of participants in neuroimaging studies. For instance, the study of Nelson et al. (2007) used only 9 novices and 10 experts, and the study of Fugelsang and Dunbar (2005) employed only 14 subjects. While it is becoming increasingly common to find studies with 15 or 20 subjects (or even more) per group, the number of subjects generally remains modest in neuroimaging studies, given the substantial costs often related to using a device such as fMRI and the potential challenge of recruiting many subjects of a given population. As we will discuss in the subsection on the methods used for data analysis, the fact that a study has a small sample size does not mean that its results are necessarily not generalizable to the population. There are in fact certain types of analysis, such as random effects analysis (also called second-level analysis) that allow, to some extent, a generalization of the results obtained from a limited sample of subjects to a larger population. In general, researchers agree that a sample of 12 subjects is sufficient to obtain a relatively good statistical power and that a larger sample including more than 24 subjects rarely presents sufficient statistical advantages to justify the additional effort and expenses incurred (Desmond & Glover, 2002). For studies involving more than one group of subjects, having more than 20 subjects per group did not significantly improve the brain activation maps obtained by data analysis (Murphy & Garavan, 2004).

Choosing the most appropriate brain imaging technique to test research hypotheses

Several brain imaging techniques exist for measuring a signal correlated with brain activity. Each technology holds advantages and disadvantages. Positron emission tomography (PET) can measure the local variation of blood flow (which may be useful to answer research questions related to the physiological response to brain activation), but this technology requires the injection of radioactive markers into the blood (Reivich et al., 1979). Another disadvantage is that the PET does not offer a spatial resolution equal to that of fMRI. Electroencephalography (EEG) (Berger, 1929) has an excellent temporal resolution and directly measures the electrical activity of the brain, but does not allow precise localization of activations. Magnetoencephalography (MEG) (Cohen, 1972) provides excellent spatial and temporal resolution and is also able to directly measure the variation of magnetic fields induced by action potentials of neurons. However, this technology does not measure the activity of subcortical regions such as the anterior cingulate cortex that seems to play an important role in science learning. Optical imaging, or optical tomography (Maki et al., 1995), allows the localization of activated brain regions, is less sensitive to head movement than other techniques and is also relatively quiet, but it has an inferior spatial resolution than fMRI and, like the MEG, does not allow us to detect subcortical activations. We chose fMRI because it is the only noninvasive imaging technique available (i.e. that does not require the use of radioactive markers like PET) to study the activation of deep regions such as the anterior cingulated cortex.

Having been in use only since the early 1990s (Kwong et al., 1992; Ogawa et al., 1990, 1992), fMRI is a recent technology. The device is composed of a powerful superconducting magnet (1.5 to 3.0 Tesla, and sometimes more), magnetic gradients for spatial localization, and generators of electromagnetic waves also acting as antennas to capture the signal. The principle of fMRI is based on the fact that we can observe a localized increase in concentration of oxygenated hemoglobin (called hemodynamic response) upon activation of a brain region. Since the oxygenated and deoxygenated hemoglobins do not have the same magnetic properties, we can measure signal variation when the concentration of oxy-hemoglobin changes due to a change in brain activity (Buckner, 1998).

The fMRI device used for our research is a Siemens TRIO TIM of 3 Tesla and contains a 12-channel antenna. This device is located at the Unité de neuroimagerie fonctionnelle (UNF) of the Institut universitaire gériatrique de Montréal (IUGM).

Designing a cognitive task that meets the constraints related to the use of brain imaging

The use of fMRI imposes constraints to the kind of questions we can ask to subjects in the fMRI scan (Amaro & Barker, 2006; Huttel, Song, & McCarthy, 2004; Mazoyer, 2001; Ward, 2010). First, since the scan emits a loud noise during image acquisition, it is difficult to use auditory stimuli. Thus, in general, visual stimuli (presented on a mirror that projects a screen image) are used. Then, since participants must remain supine with their heads completely still during image acquisition (movement of more than 2 mm may affect the data analysis), we usually avoid asking them to respond orally to questions, which could make the head move. Thus, we favor multiple-choice questions, which participants need only press a button to answer. Moreover, since the variation in measured signal can be less than 2% and the signal-to-noise ratio is not very high, it is necessary to have at less 20 stimuli in each of the studied conditions to allow detection of statistically significant differences. Finally, due to delay between neuronal activations and blood oxygenation variation, it is important to allow a sufficient length of time for presentation of stimuli and rest periods.

The cognitive task given to participants of our study is to determine (by pressing either button) whether the electric circuits presented on the screen are correct or incorrect, i.e. consistent with what would happen in a real life situation. The stimuli used in the task are composed of simple electric circuits designed to highlight the common misconception “a single wire is sufficient to light a bulb”. More precisely, three types of electric circuits are presented: naive circuits in agreement with the misconceptions of the novices in which a single wire is sufficient to light a bulb, scientific circuits in accordance with scientific knowledge (two wires needed to light a bulb) and control circuits (the bulb lights, even if the wire is broken) in which novices and experts would be expected to answer in the same way.

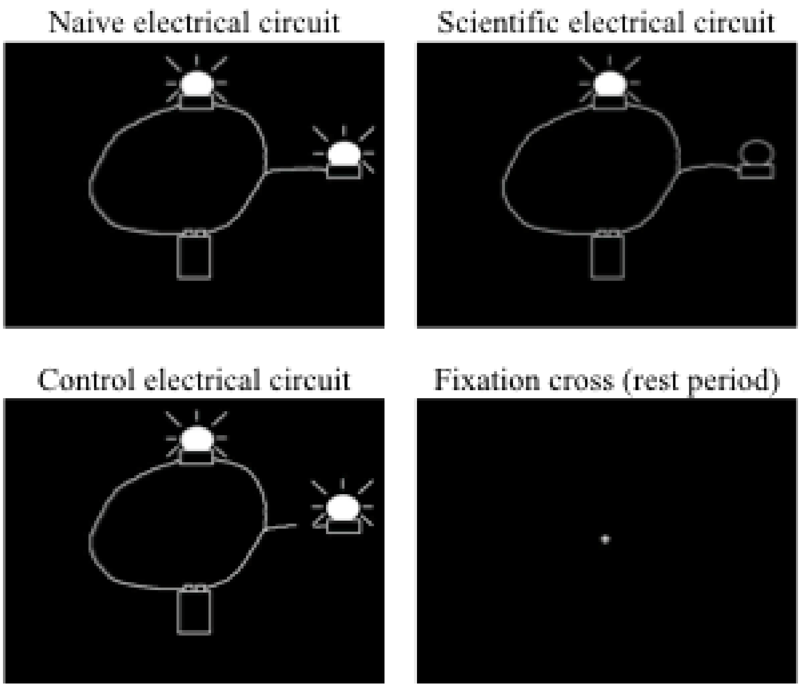

Figure 1. Examples of electric circuits used to study conceptual change with fMRI

The stimuli are presented according to an event-related design (Buckner, 1998; Bandettini & Cox, 2000) consisting of randomly alternating naive, scientific and control stimuli. Firstly, we present a circuit without any battery for 1.5 seconds. Secondly, a battery is added to the circuit, and some light bulbs turn on whilst others remain off. The image of the electric circuit with light bulbs turned on or off is shown until the participant responds by pressing a button (correct circuit = index finger of the right hand; incorrect circuit = middle finger of the right hand).

After obtaining the participant's answer, a fixation cross is presented for 2.5 seconds or 3.0 seconds. These periods of rest alternate between 2.5 seconds and 3.0 seconds to avoid habituation of the brain at a fixed period of rest. If the participant does not answer after 2.5 seconds, the image of an electrical circuit with a battery switches automatically to the rest period (i.e. the image of a fixation cross). In addition to the rest periods between stimuli, others are also included in the task and last 6.0 seconds each.

The task is divided in two equivalent series composed of different types of stimuli. Throughout the two series, there are 20 stimuli in each condition (naive, scientific and control circuits) and 20 rest periods.

Preprocessing and analyzing data in the most appropriate way

After having defined operational research hypotheses, determined participants' selection criteria to obtain relatively homogeneous groups, chosen the best imaging technique to answer the hypothesis, and developed a cognitive task that respects the constraints related to brain imaging, a discussion of how the data are preprocessed and analyzed remains to be done. In order to achieve valid comparisons, the images must be corrected for head movement. To achieve this, we use the algorithm developed by Friston, Williams, Howard, Frackowiak, and Turner (1996) of the analysis software package SPM8 (Wellcome Department of Imaging Neuroscience London, UK) that considers the brain to be a rigid body. This algorithm applies spatial transformations according to six parameters (three are translations in x, y and z, and three are linked to the three possible angles of head rotation) in order to align the images of a series to a reference image (any image within the series). By performing a correction of movement, we ensure that a region of the brain is at the same position throughout the period of data acquisition, which is essential for the statistical analysis that follows the preprocessing of brain images.

To average the data from many subjects and to compare their brain activity, we must carry out a normalization of the individuals' brains. Indeed, since we want to compare the activation of specific regions despite the fact that each brain is shaped differently, it is necessary to modify the brain images of each subject, so they all show a brain of the same width, length, etc. The software that performs the normalization compares the contours of a reference image and the contours of images of the brain to be transformed. The brain of reference we use is the template of the Montreal Neurological Institute (MNI), included in SPM8. After identifying the contours, the images are normalized by the software in order to transform them into images similar to the reference image. In our research, normalization is done by using the segmentation procedure developed by Ashburner and Friston (2005).

Once movement correction and normalization of the brain images are completed, it is necessary to improve the signal-to-noise ratio by doing a smoothing of the images. This smoothing consists of distributing the signal of each voxel of the brain (a voxel is the smallest box-shaped part of a three-dimensional brain image) to their "neighbors". To do this, we spread the signal of each voxel according to a Gaussian function of a width set at 8 mm at half the height of the maximum. In addition to improving the signal-to-noise ratio by reducing the peaks of extreme intensity and increasing the value of significantly activated voxels that are surrounded by also highly activated voxels, it reduces the risk of considering artifacts as regions to be significantly activated. Another significant advantage of smoothing is to facilitate the detection of regions that are activated in several subjects. Indeed, since every brain is different, smoothing avoids a situation where a voxel is not significantly activated because the brain region of interest does not lie exactly in the same voxels for each subject.

Once the data have been preprocessed (i.e. corrected for movement, normalized and smoothed), we can assess whether or not a brain region is significantly more activated in a particular condition of the cognitive task compared to another. This comparison is often performed by using a t-test. Since we do not want to know the brain activity of only one individual, but rather that of a group, we must obtain the average results of all participants in both groups. To do so, a first-level analysis, also known as a fixed-effects analysis (or within-subject analysis) is conducted using the analysis software package SPM8. This analysis combines the images obtained during series 1 and 2. This way, we obtain for each subject a statistical map and the desired statistical comparisons. This analysis allows us to examine the brain activity of each individual.

To determine the brain activity of a group or to compare the brain activity of two groups, it is not desirable to perform a first-level analysis, since this type of analysis, appropriate for within-subject analysis, does not allow a generalization of the results to an entire population (Huettel, Song, & McCarthy, 2004). In fact, since first-level analysis is very sensitive to outliers in the data, it is not possible to extrapolate the results to larger populations. If, for example, we have three subjects, from a sample of ten, who react strongly to stimuli by showing strong brain activations in certain regions, a first-level analysis would derive statistically significant results for the whole group, even though seven of the subjects respond only weakly to the task.

To resolve this problem, we use second-level analysis, also called random-effects analysis. To detect a significant statistical difference using this type of analysis, it is necessary that the observed effect is significantly present in all subjects, because those with strong reactions to the task cannot compensate for those who react weakly. This type of analysis is more appropriate when we want to generalize the results obtained to an entire population. It is this type of analysis that we use to compare the group of experts with the group of novices in science.

Conclusion

As discussed in the first part of this paper, brain imaging offers unprecedented and promising opportunities for conceptual change research. This technique allows measuring a variable that has never been measured before (brain activity) and can contribute significantly to the development of knowledge about conceptual change. Already, early studies in this emerging field provide the opportunity to question the commonly held view that conceptual change involves the removal or restructuration of prior knowledge, and to examine some new concepts, such as the concept of inhibition.

Despite being an extremely interesting technique, the use of brain imaging imposes many constraints. In the second part of this paper, we presented how the difficulties caused by these constraints have been overcome in an ongoing study in which fMRI is being used to study the brain-based mechanisms of conceptual change in electricity. One of the most challenging aspects in this ongoing research project has been the development of a cognitive task that meets the constraints imposed by this technology, while still being informative for the field of conceptual change. Inspired by the literature in education research about misconceptions relating to electric circuits, we developed a cognitive task based on the frequent misconception: “a single wire is sufficient to light a bulb”. This task is strongly related to an important education problem (how to change students’ misconceptions) and respects all the constraints imposed by the fMRI technology. For example: questions are limited to visual stimuli, subjects can only answer to multiple-choice questions by pushing buttons (is the electric circuit correct or not?), and so on.

Although it is pertinent and feasible to study conceptual change with fMRI, this technology has its limitations. For instance, since almost all fMRI studies exclude left-handed individuals, the results can only be generalized to a limited portion of the population (right-handed individuals). Furthermore, when a study, like ours, focuses on only one gender, the results cannot be generalized to both genders. Another limitation is that, to respect all constraints imposed by using fMRI, a study using brain imaging must target only a limited number of variables (or factors) and must neglect the others, even if they are known to be important, which leads to a kind of "methodological reductionism" that can't be avoided. Finally, the quality of the interpretation of the data (and potential implications for education) is limited to our actual understanding of how the brain works. We certainly know more about the brain today than a few years ago, but the brain is complex, and we are still far away from a complete understanding of its functions. All these limitations mentioned above lead to think that neuroimaging can't and won't ever replace traditional methods in education research. Brain imaging can be used as a powerful tool that complements the ones usually used by education researchers, not replaces them.

Over the next years, we think that the development of fMRI cognitive tasks relating to science education will play an important role in research. When researchers will have access to more cognitive tasks relevant to the study of conceptual change, the research process will be significantly facilitated because these cognitive tasks (like standardized tests) will not have to be built from scratch by researchers and will be used and reused in different research contexts to achieve different studies.

In addition to the development of fMRI-compatible science education tasks, we think that the researchers should actually focus their research on the brain mechanisms linked to science expertise. The study of neural correlates of expertise in reading and counting has been a successful first step toward a better understanding of how the brain learns to read and count and how teachers could help children to wire their brain to be able to read and count. We think that identifying the neural correlates of science expertise will be the first step to go further in our understanding of the brain-based mechanisms relating to science education.

For instance, researchers could compare the brain activity of novices and experts in different domains such as mechanics, chemistry and thermodynamics and could study different degrees of expertise in science (not only novices vs. experts, but also, for example, novices vs. semi-experts or experts vs. "super experts"). When the neural correlates of scientific expertise are identified, we think it would be a lot easier to interpret the neuroimaging data regarding, for example, the effects of a particular teaching strategy or the effects of various pedagogical approaches, and, especially, to link these data to science education in order to improve science teaching.

Many challenges must be overcome over the next years to develop that neuroscientific approach we tried to describe in this paper, but the potential implications for science education research, for science teachers and for children learning science could be substantial.

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Manyetik rezonans görüntülemeyi (MRG) kullanarak kavramsal gelişimi inceleme: Neden ve nasıl?

Fonksiyonel manyetik rezonans görüntüleme (fMRG) gibi zihin görüntüleme tekniklerinin kullanımının eğitim araştırmalarında giderek artan ortak kullanımı olmasına rağmen şu ana kadar fen öğrenimine yönelik oldukça az sayıda çalışma bu teknolojinin avantajını kullanmıştır. Bu çalışma, elektrik kavramlarındaki kavramsal değişimle ilgili beynin mekanizmalarını belirlemeye çalışan fMRG çalışmaları üzerinde devam etmekte olan epistemolojik ve yöntemsel çerçevenin ne olduğunu sunarak fen öğrenimiyle ilişkilendirilebilecek zihin görüntüleme çalışmalarının tasarlanması ve uygulamasını kolaylaştırmayı amaçlamaktadır. Bu amaca ulaşmak için makalenin ilk kısmında, kavramsal değişimde fMRG'yi neden kullandığımızı ilgili literatürü sunarak açıklayacağız. İkinci kısımda ise zihin görüntülemenin fen eğitimiyle ilgili araştırmaya nasıl uygulanabileceğine yönelik devam etmekte olan çalışmaların yöntemini sunacağız.

Anahtar kavramlar: zihin görüntüleme, kavramsal değişim, eğitsel nöro-bilim, nöro-eğitim, fen eğitimi