MIND, BRAIN, AND EDUCATION

Differences in Brain Activation Between Novices and Experts in Science During a Task Involving a Common Misconception in Electricity

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ABSTRACT— Science education studies have revealed that students often have misconceptions about how nature works, but what happens to misconceptions after a conceptual change remains poorly understood. Are misconceptions rejected and replaced by scientific conceptions, or are they still present in students' minds, coexisting with newly acquired scientific conceptions? In this study, we use functional magnetic resonance imaging (fMRI) to compare brain activation between novices and experts in science when they evaluate the correctness of simple electric circuits. Results show that experts, more than novices, activate brain areas involved in inhibition when they evaluate electric circuits in which a bulb lights up, even though there is only one wire connecting it to the battery. These findings suggest that experts may still have a misconception encoded in the neural networks of their brains that must be inhibited in order to answer scientifically.

For at least 30 years, researchers in science education have studied people's spontaneous conceptions about how nature works (Duit & Treagust, 2012). These studies have shown that these intuitive conceptions are often opposed to the scientific knowledge taught in schools (Liu, 2001). For example, many people believe that heavier objects fall faster (even in the absence of air resistance, which is false), or that it is warmer in summer because the Sun is closer to the Earth (which is also false). If these misconceptions were not so difficult to change, they would not be a problem. However, one of the most robust findings of science education research about misconceptions is that they are particularly hard to change (Duit & Treagust, 2012; Periago & Bohigas, 2005; diSessa, 2006; Vosniadou, 2012; Wandersee, Mintzes, & Novak, 1994), which poses a serious challenge for science teachers who try to change their students' misconceptions into scientifically valid knowledge.

The problem of the persistence of nonscientific conceptions during science education has led to a field of research called "conceptual change" (for a review, see Duit & Treagust, 2012; diSessa, 2006; Vosniadou, 2008, 2012). This field tries to understand why students' misconceptions are hard to change, what changes during conceptual change, and how to facilitate the learning of unintuitive scientific concepts. Over the years, researchers in this field have proposed several theoretical models to answer these questions (Carey, 2009; Chi, 1994; Giordan & DeVecchi, 1987; Mortimer, 1995; Nussbaum & Novick, 1982; Posner, Strike, Hewson, & Gertzog, 1982; diSessa, 1993; Smith, 2007; Stavy et al., 2006; Vosniadou, 1994).

Most of these models (Carey, 2009; Chi, 1994; Duit & Treagust, 2003; Giordan & DeVecchi, 1987; Nussbaum & Novick, 1982; Posner et al., 1982; Smith, 2007; Vosniadou, 1994) share a common postulate according to which conceptual change is hard to achieve not only because students must abandon their initial misconceptions, but also because they must radically restructure their knowledge structure in order to accommodate new scientific concepts and theories. For example, according to Duit and Treagust

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(2003), misconceptions are tangled in a broad conceptual system and, consequently, the "conceptual structures of the learners have to be fundamentally restructured in order to allow understanding of the intended knowledge, that is, the acquisition of science concepts" (p. 673). According to another researcher, Vosniadou (2012), students' conceptions are caused and supported by epistemological and ontological presuppositions that must be replaced during conceptual change. Finally, for Chi (1994), conceptual change necessitates an important reorganization of learners' knowledge structures in which concepts must change their meaning and be reassigned to a different ontological category.

As argued by Shtulman and Valcarcel (2012), implicit to the idea of knowledge restructuring is the idea that learners' initial knowledge systems, which are assumed to have been considerably altered during conceptual change, no longer exist after a conceptual change, since they have been replaced by something else. Indeed, in most conceptual change models, the coexistence of scientific and nonscientific conceptions in learners' minds is either implicitly rejected or presented as an intermediate step, suggesting that conceptual change is occurring, but has not been achieved yet (see Posner et al., 1982).

Recently, a number of findings have challenged the idea that misconceptions disappear definitively after a conceptual change. For instance, two studies have pointed out that naive modes of thought about how nature works, usually only common during childhood, can re-emerge later in life. Indeed, seniors with a decreasing inhibition capacity due to Alzheimer's disease return to teleological explanations (Lombrozo, Kelemen, & Zaitchik, 2007) and animist thinking (Zaitchik & Solomon, 2008) to explain how nature works. Moreover, other studies have shown that healthy adolescents (Babai & Amsterdamer, 2008), adults (Shtulman & Valcarcel, 2012), and even professional scientists (Goldberg & Thompson-Schill, 2009; Kelemen, Rottman, & Seston, 2012) need more time to correctly answer questions related to misconceptions, as if they needed to inhibit (i.e., control, deactivate, or suppress) a spontaneous and appealing, albeit wrong, answer. All of these studies suggest that misconceptions and naive thinking about nature have possibly never disappeared from the brains of adolescents, adults, seniors, and professional scientists and, therefore, need to be inhibited.

Although the idea that learning certain scientific concepts requires fighting against our natural tendencies and intuitions is not new (Bachelard, 1938), the concept of inhibition has rarely been used in conceptual change research. There are, however, a few notable exceptions. For instance, Kwon and Lawson (2000) have shown that, among different students' characteristics (such as planning ability, age, disembedding ability, and mental capacity), the ability to inhibit is the single best predictor of the capacity to improve their understanding of scientific concepts related to air pressure. There is also a pilot functional magnetic resonance imaging (fMRI) study, conducted by Dunbar, Fugelsang, and Stein (2007), that shows differences in brain activation between novices and scientific experts when they evaluate the correctness of videos showing balls of different sizes falling at different speeds. According to the authors' interpretation, the results support the idea that experts still need to inhibit the misconception that "heavier balls fall faster," even if they most likely overcame it several years earlier.

The concept of inhibition refers to the cognitive ability to resist a habit or a spontaneous and tempting response or strategy. At a neural level, it refers to the capacity of a neural network to deactivate another neural network that would otherwise be activated. A number of neuroimaging studies have used cognitive tasks (Stroop, counting Stroop, go/no-go, etc.) where inhibition is needed to overcome a prepotent but inappropriate response. These studies have shown that the anterior cingulate cortex (ACC), the ventrolateral prefrontal cortex (VLPC), and the dorsolateral prefrontal cortex (DLPC) are more activated when inhibition is required (Bush et al., 1998; Menon, Adleman, White, Glover, & Reiss, 2001; Monchi, Petrides, Petre, Worsley, & Dagher, 2001; Nathaniel-James, Fletcher, & Frith, 1997). According to Botvinick (2007), the ACC is associated with error detection and decision making. It detects that a particular situation or task requires higher cognitive control. Consequently, the ACC may be the brain region that triggers the inhibition process, while the DLPC and the VLPC may be more directly responsible for the inhibition of spontaneous answers or strategies (Aron, Robbins, & Poldrack, 2004; De Neys, Vartanian, & Goel, 2008; Liddle, Kiehl, & Smith, 2001; MacDonald, 2000).

This article aims to contribute to the debate about what happens to misconceptions after a conceptual change (Shtulman & Valcarcel, 2012). Are they rejected and replaced by scientific conceptions, or are they still present in the minds of students, coexisting with newly acquired scientific conceptions? In order to answer this question, we propose to use fMRI to observe the differences in brain activation between novices (with misconceptions) and experts in science (seemingly without misconceptions because they answered correctly) when they respond to questions involving a common misconception. On the basis of studies discussed previously, we hypothesize that scientific experts will show more activation than novices in brain areas involved in inhibition such as the ACC, the DLPC, and the VLPC (Bush et al., 1998; Menon et al., 2001; Nathaniel-James et al., 1997) because they need to inhibit a misconception that is still encoded in their brains' neural networks.

Since students' misconceptions in electricity are among the most frequent and persistent (Wandersee et al., 1994), and because brain mechanisms of expertise in that domain have never been studied, we have chosen to identify the differences in brain activation between novices and experts during a task based on a common misconception in electricity. This misconception, especially frequent at the beginning of conceptual change, states (wrongly) that only one wire is sufficient to light a bulb (Çepni & Keleş, 2006; Periago & Bohigas, 2005). The task will be described in the next section.

METHODS

Participants

Twenty-three right-handed men, either novices or experts in science, took part in the study. These men were students of two Francophone universities in Montreal, Quebec, Canada. All participants completed their pre-university education in the province of Quebec, Canada, except for two novices from Switzerland and France, and one expert from Costa Rica. Women were excluded from both groups to avoid a possible inter-subject variability due to gender (Grabner et al., 2007).

Novices ($n = 12$; between ages 19 and 30; $M = 22.9$; $SD = 3.5$) were undergraduate students in humanities (history, politics, philosophy, etc.) who had never taken any optional science classes and therefore had only limited science education. To be certain that the novices had the misconception that "only one wire is sufficient to light a bulb," they answered a questionnaire several days before their fMRI scan, which included questions that were similar to those used in the fMRI phase. A total of 20 of 48 volunteers (42%) had the misconception that electric circuits, with only one wire connecting the battery and the bulb, are correct if the bulb lights up and are incorrect if the bulb does not. Of these 20 volunteers, 15 had an fMRI scan. During the task performed in the scan, 12 of them had incorrect answers for more than 90% of the questions related to the misconception; the data of the three other participants were excluded from the analysis. To limit inter-subject variability due to differences in academic performances, novices with an average university score below 2.3 or above 4.1 out of 4.3 (i.e., below C + and above A) were excluded from the study.

Experts ($n = 11$; between ages 20 and 27; $M = 22.1$; $SD = 3.5$; no significant differences between the ages of the novices and experts: $t(21) = 0.59, p = .56$) were undergraduate students in physics who had taken optional science courses during their high school and college education. Of the 15 volunteers who answered the questionnaire, 13 responded correctly to the questions related to electric circuits and did not seem to have the misconception "one wire is sufficient to light a bulb." The data of one subject were excluded from the analysis because his answers in the scan were not correct for at least 90% of the trials. To limit inter-subject variability due to differences in academic performances, experts with an average university score below 2.3 or above 4.1 of 4.3 (i.e., below C+ and above A) were excluded from the study.

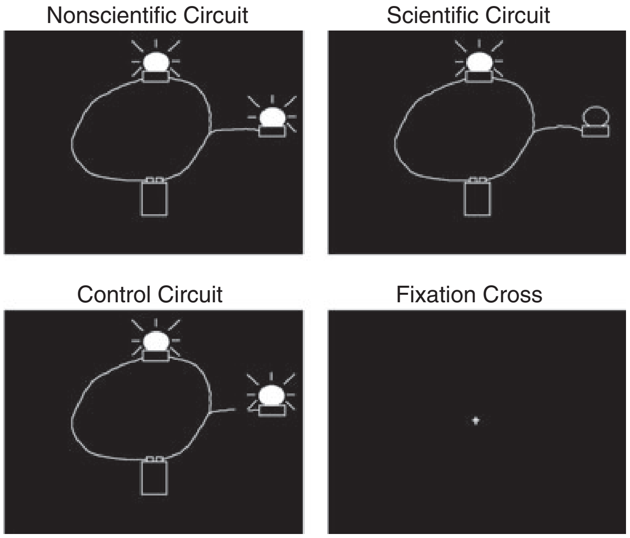

Fig. 1. Examples of stimuli used in the electric circuit task.

Participants reported no abnormal neurological history. Written informed consent for all participants was obtained prior to the experiment, and the study was approved by a local ethics committee (Comité d'éthique mixte de la recherche de l'Institut universitaire de gériatrie de Montréal, Quebec, Canada).

Task

Participants were asked to determine (by pressing one of the two buttons) if the images of electric circuits presented on the screen were correct or incorrect (see Figure 1). The stimuli were designed to highlight the misconception that a single wire is sufficient to light a bulb. Three types of electric circuits were presented: nonscientific circuits representing novices' misconception that one wire can light a bulb, scientific circuits conforming to scientific knowledge, and control circuits in which novices and experts were expected to respond similarly (the bulb cannot light up when the wire connecting the battery to the bulb is broken). Control circuits were used in the task to ensure that the task was understood by both experts and novices, and also because they did not involve the inhibition of a misconception. All circuits included two bulbs, but the position of the bulbs, the place where the single wire was connected to the circuit, and the length of the wires were different in each circuit. Participants were told that a single line in the electric circuit represented a single wire.

The stimuli were randomly presented according to an event-related design (Bandettini & Cox, 2000; Buckner, 1998) consisting of nonscientific, scientific, and control stimuli. Electric circuits were presented without batteries for 1.5 sec. Next, a battery was added to the circuit, and some bulbs lit up while others did not. The images of electric circuits with the bulbs turned on or off were presented until the participant

Table 1
Mean Accuracy (out of 20) and Reaction Time (in sec) of Novices and Experts for Control, Scientific, and Nonscientific Circuits

	Novices				*Experts*			
	Accuracy		*Reaction time*		*Accuracy*		*Reaction time*	
Circuits	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Control	19.6	0.8	2.653	0.189	19.6	0.7	2.430	0.170
Scientific	0.8	1.2	2.885	0.351	18.6	0.7	2.432	0.223
Nonscientific	0.4	0.8	2.799	0.275	19.7	0.9	2.375	0.225

answered by pressing a button (correct = index finger of the right hand; incorrect = middle finger of the right hand). After obtaining the participant's response, a fixation cross was presented for 2.5 or 3.0 sec; rest periods alternated between 2.5 and 3.0 sec to avoid brain habituation to a fixed rest period. Stimuli were divided in two equivalent series. Throughout the two series, there were 20 stimuli for each condition (nonscientific circuits, scientific circuits, and control circuits). In addition to rest periods between stimuli, 20 visual fixation periods of 6 sec were placed randomly in the series. A pause of about 3 min was given to the participant between the two series. The task also included movies presenting balls of various sizes falling to the ground, inserted randomly between the circuits. In this article, for the purpose of concision, we will focus only on the data related to the electric circuits.

Procedure

Participants were taken to a simulation room with a computer on a desk and an fMRI Simulator™ (Psychology Software Tools, Inc., Sharpsburg, PA, United States). After watching a short video of instructions on the computer, they did a practice task, which was composed of 10 electric circuits similar to those used in the fMRI task. Next, participants did the same practice task a second time, but in the fMRI simulator. After this simulation, participants moved into the fMRI room for the data acquisition. Structural images were obtained at the end of the two functional image series. Participants were explicitly informed not to move during the simulation and the fMRI scan.

Image Acquisition

Data were acquired with a Siemens 3.0 Tesla MAGNETOM Trio TIM using a 12-channel head coil. Functional images were obtained with a gradient echo EPI sequence (TR = 2,000 msec, TE = 30 msec, FA = 90°, matrix size = 64 × 64, voxel size = 3 mm × 3 mm × 3 mm, number of slices = 33, slice gap = 25%, ascending, AC-PC line orientation, whole brain scanned). The first two images were automatically eliminated by the system. Structural images were obtained with a MPRAGE sequence (TR = 2,300 msec, TI = 900 msec, TE = 2.98 ms, FA = 9°, matrix size = 240 × 256, voxel size = 1 mm × 1 mm × 1.2 mm, number of slices = 160, interleaved, sagittal orientation). Cushions were arranged around participants' heads to minimize head motion. Stimuli were presented with E-Prime 2.0 software (Psychology Software Tools, Inc.) via a mirror and a projection system. Subjects' responses were collected with an 8-Button Bimanual Fiber Optic Response Pad from Current Designs, Inc., Philadelphia, PA, United States.

Statistical Analysis

Preprocessing and data analysis were performed using SPM8 (Wellcome Department of Imaging Neuroscience, London, UK). Functional images were realigned with mean image (Friston, Williams, Howard, Frackowiak, & Turner, 1996), spatially normalized into the standard MNI space using the segmentation method implemented in SPM8 (Ashburner & Friston, 2005), and smoothed using a Gaussian kernel of 8 mm FWHM. The general linear model was used for modeling the data. More precisely, trial-related activity was modeled by convolving a vector of trial onsets with a canonical hemodynamic response function. The six movement parameters were also included in the model as regressors of no interest. A first-level analysis was used to average the functional series of each participant. At the group level, a second-level analysis (random effect analysis, *t*-test) was performed to obtain the contrasts of interest. The rationales behind the use of these preprocessing steps and the choice of a second-level analysis are explained extensively in an article published by Masson, Potvin, Riopel, Brault Foisy, and Lafortune (2012).

RESULTS

Behavioral Data

Table 1 presents the behavioral data associated with the task. Experts correctly answered most of the control circuits ($M = 19.6$ of 20; $SD = 0.7$), scientific circuits ($M = 18.6$ of 20; $SD = 0.7$), and nonscientific circuits ($M = 19.7$ of 20; $SD = 0.9$). As expected, novices did not perform well for the scientific circuits ($M = 0.8$ of 20; $SD = 1.2$) and nonscientific circuits ($M = 0.4$ of 20; $SD = 0.8$), but correctly answered most of the control circuits ($M = 19.6$ of 20; $SD = 0.8$). The difference in accuracy between experts and novices was significant for the scientific, $t(21) = 43.47$, $p < .001$, and nonscientific circuits, $t(21) = 54.56$, $p < .001$, but was not significant for the control circuits, $t(21) = -0.12$, $p = .904$.

Reaction time was significantly lower for experts than novices for control circuits, $t(21) = 2.953$, $p = .008$, scientific circuits, $t(21) = 3.649$, $p = .001$, and nonscientific circuits, $t(21) = 4.027$, $p = .001$. For novices, there was no difference in reaction time between scientific and nonscientific circuits, $t(11) = -1.162$; $p = .270$; however, the differences between nonscientific and control circuits, $t(11) = 2.404$; $p = .035$, and between scientific and control circuits, $t(11) = 3.019$; $p = .012$, were significant. For experts, there was no significant difference in reaction time between the conditions.

Neuroimaging Data

Table 2 shows the brain areas that are more activated for experts and novices for each type of electric circuit compared to rest periods of visual fixation ($p < .0005$, uncorrected, minimum 10 voxels). When evaluating the correctness of control circuits, experts activate their right angular gyrus/middle temporal gyrus (BA 39) significantly more than novices, whereas novices do not activate any brain area significantly more than experts. However, when they evaluate scientific circuits, novices show more activation in the left DLPC (BA 46) compared to experts, whereas experts still activate their right angular gyrus/middle temporal gyrus (BA 39) more than novices. When evaluating nonscientific circuits, novices do not activate any brain area significantly more than experts. However, experts activate a number of regions more than novices: in the posterior part of the brain, the right angular gyrus/middle temporal gyrus (BA 39) is more activated, and in the anterior part of the brain, activations are found in the left VLPC (BA 45), the left DLPC (BA 9), and the right ACC (BA 32). The latter activation survives to an FWE-corrected threshold of $p < .05$ at cluster-level (using $p < .0005$ uncorrected at the voxel level, minimum 10 voxels). The same brain regions (DLPC, VLPC, AAC, and angular gyrus/middle temporal gyrus) remain more activated for experts than novices when data from nonscientific and scientific circuits are merged. Finally, the left DLPC remains more activated for novices than experts when data from nonscientific and scientific circuits are merged.

Figure 2 presents the results of this experiment by using "glass brain images" (the gray and white squared images shown in the middle of the figure) produced by SPM8. Each glass brain shows, with only one image, all significant activations found in all slices of the brain. The left part of these images represents the posterior section of the brain, and the right part, the anterior section. This figure highlights the fact that the differences in brain activations between experts and novices are limited to only one brain area for the control circuits (the angular gyrus/middle temporal cortex is more activated for experts) and scientific circuits (the DLPC is more activated for novices and the angular gyrus/middle temporal cortex is more activated for experts), but the differences are numerous for nonscientific circuits. Indeed, experts significantly activate four brain areas more than novices: the angular gyrus/middle temporal gyrus, the VLPC, the DLPC, and the ACC.

Table 3 shows the brain areas significantly more activated in one type of electric circuit compared to another. No significant differences in activation are observed between conditions for experts, except for the comparison of *nonscientific circuits > scientific circuits*, where experts activate more the right occipitotemporal cortex (BA 19) and the left superior parietal lobe/precuneus (BA 7). Concerning the novices, no significant activations are observed for the comparison of *nonscientific circuits > scientific circuits*, but a number of brain areas are more activated for scientific circuits than for nonscientific circuits. These areas include the left DLPC (BA 9/10) and the right ACC (BA 32). The contrast between *nonscientific circuits > control circuits* reveals activation in the left lingual/parahippocampal gyrus.

DISCUSSION

This study aims to test the hypothesis that scientific experts might still have the misconception that "one wire is sufficient to light a bulb" encoded in the neural networks of their brains. If they do, experts should need to inhibit it in order to answer correctly. Consequently, more activation in brain areas usually involved in inhibition (i.e., the VLPC, the DLCP, and the ACC) should be found in experts compared to novices.

Brain Areas Related to Scientific Expertise and Inhibition

The results regarding nonscientific circuits (see Table 2 and Figure 2) support this hypothesis. Indeed, when they evaluate this type of circuit, experts, more than novices, activate brain areas related to inhibition such as the VLPC, the DLPC, and the ACC (see Bush et al., 1998; Chen, Muggleton, Tzeng, Hung, & Juan, 2009; Liddle et al., 2001; Menon et al., 2001; Nathaniel-James et al., 1997; Rubia et al., 2001). However, when they evaluate scientific circuits, experts activate only one brain area (the angular gyrus/middle temporal gyrus) significantly more than novices, which seems to be in opposition to the inhibition hypothesis.

A possible explanation for these results is that inhibition might only be necessary when experts encounter questions related to nonscientific circuits, but not when they encounter questions related to scientific circuits. This could mean that the spontaneous conception that experts may have to inhibit is not a general conception that applies to all situations where

Table 2
Brain Areas Significantly More Activated in Experts and Novices for Each Type of Electric Circuit Compared to Rest Periods of Visual Fixation

Area	*x*	*y*	*z*	*t*
Experts > novices				
Control circuits				
R angular gyrus/middle temporal gyrus (BA 39)	45	−72	15	5.41
Scientific circuits				
R angular gyrus/middle temporal gyrus (BA 39)	48	−78	15	4.84
Nonscientific circuits				
R angular gyrus/middle temporal gyrus (BA 39)	48	−78	15	6.12
L anterior cingulate cortex (BA 32)*	−6	45	24	5.88
L ventrolateral prefrontal cortex (BA 45)	−48	27	0	5.09
R dorsolateral prefrontal cortex (BA 9)	6	57	27	4.53
Nonscientific circuits + scientific circuits				
L anterior cingulate cortex (BA 32)*	−9	45	21	5.63
R angular gyrus/middle temporal gyrus (BA 39)	48	−78	15	5.62
R dorsolateral prefrontal cortex (BA 9)	3	57	27	4.95
L ventrolateral prefrontal cortex (BA 45)**	−48	24	0	3.81
Novices > experts				
Control circuits				
No significant activations				
Scientific circuits				
L dorsolateral prefrontal cortex (BA 46)	−30	39	0	5.34
Nonscientific circuits				
No significant activations				
Nonscientific circuits + scientific circuits				
L dorsolateral prefrontal cortex (BA 46)	−30	39	3	5.56

Note. $p < .0005$, uncorrected, minimum 10 voxels, second-level analysis (random effect analysis, t-test), MNI coordinates in mm, L = left, R = right. $*p < .05$ FWE-corrected at cluster-level. $**p < .001$, minimum 7 voxels.

a bulb is connected to a battery with only one wire, but a more context-specific tendency to consider that it is natural that all the bulbs light up when a battery is connected to the circuit (even if the bulb is connected with a single wire to the battery). According to this explanation, saying that this natural situation is incorrect may require inhibition.

Another explanation is that differences in brain activation between experts and novices might be due not only to inhibition, but also to error detection and conflict monitoring mechanisms, which can involve similar brain areas as inhibition, such as the ACC and the prefrontal cortex (Botvinick, 2007). Indeed, when the brain detects that a situation is incorrect, the ACC, and sometimes the prefrontal cortex, can be activated, regardless of the fact that inhibition is required or not. Since responses provided by experts and novices differ (experts respond that the nonscientific circuits are incorrect and that the scientific circuits are correct, whereas the novices respond the opposite), it appears plausible that error detection and conflict monitoring mechanisms play a role in the differences in brain activation observed between novices and experts. However, these error detection mechanisms, if not combined with inhibition mechanisms, cannot completely explain the results of this study. Indeed, if the differences in activation were due only to the type of response provided by participants, the data would reveal more activation for novices in the prefrontal cortex and the ACC for scientific circuits, where the responses of novices and experts differ (novices respond that the circuits are not correct, whereas experts say they are), but this is not the case. Novices activate only one region, the DLPC (BA 46), significantly more than experts when they evaluate scientific circuits. On the contrary, for nonscientific circuits where the responses of novices and experts also differ (experts respond that the circuits are not correct, whereas novices say they are), experts activate not only one, but four brain regions significantly more than novices, including the regions usually associated with inhibition: the ACC (BA 32), the VLPC (BA 45), and the DLPC (BA 9). For this reason, it appears that error detection mechanisms cannot solely explain the results, supporting the idea that inhibition might play a role in the differences in brain activation between experts and novices.

Results presented in Table 3 (which shows brain areas significantly more activated in one type of electric circuit compared to another) also support the idea that differences in brain activation are not only due to the type of response provided by participants, but also due to inhibition mechanisms. In fact, brain activations for novices can be explained by error detection mechanisms alone, because

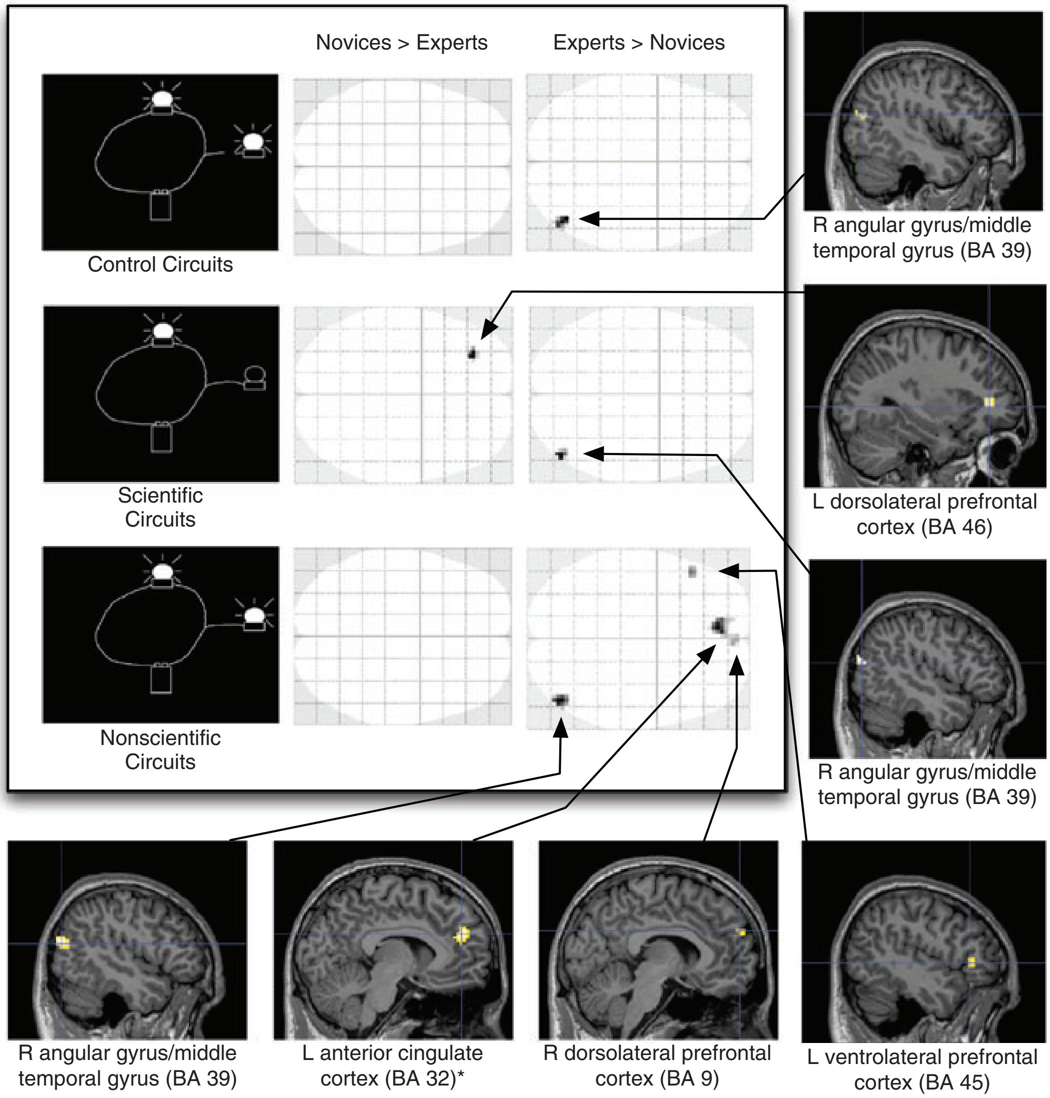

Fig. 2. Brain areas significantly more activated in experts and novices for each type of electric circuit compared to rest periods of visual fixation. ($p < .0005$, uncorrected, minimum 10 voxels, L = left; LR = left and right; R = right). *$p < .05$ FWE-corrected.

there is no inhibition involved in novices' responses (when they judge scientific circuits as being incorrect compared to nonscientific circuits as being correct, novices activate their ACC and their prefrontal cortex more). However, for experts, observed brain activations cannot be explained solely by considering error detection mechanisms because, although experts respond that nonscientific circuits are incorrect and scientific circuits are correct, we observe no significant activation in experts' brain areas involved in error detection and conflict monitoring for the contrast *nonscientific circuits > scientific circuits*. This is probably because the ACC and the prefrontal cortex are activated in both conditions. For nonscientific circuits, these brain areas are activated by error detection mechanisms (and perhaps also by inhibition mechanisms), whereas for scientific circuits, they are activated because answering correctly to scientific circuits requires inhibiting the misconception that one wire is sufficient to light a bulb. The contrast *nonscientific circuits > scientific circuits* reveals no significant differences in activation because the same brain areas are involved in both conditions.

Another interesting observation concerning the results presented in Table 3 is that no significant activation was found in experts' brains for the contrast *nonscientific circuits > control circuits*, although the nonscientific circuits might involve inhibition and the control circuits might not. This is probably because experts activate error detection and conflict monitoring mechanisms in both conditions (judged as incorrect by experts), which cancel each other. The fact that nonscientific circuits require both inhibition and error detection mechanisms and that control circuits require only

Table 3
Brain Areas Significantly More Activated in One Type of Electric Circuit Compared to Another

Area	*x*	*y*	*z*	*t*
Experts				
Nonscientific circuits > scientific circuits				
R occipito-temporal cortex (BA 19)	21	−48	−6	5.37
L superior parietal lobe/precuneus (BA 7)	−12	−51	66	5.36
Scientific circuits > nonscientific circuits				
No significant activations				
Nonscientific circuits > control circuits				
No significant activations				
Scientific circuits > control circuits				
No significant activations				
Novices				
Nonscientific circuits > scientific circuits				
No significant activations				
Scientific circuits > nonscientific circuits				
L inferior parietal lobe/lateral sulcus (BA 40)**	−54	−48	33	7.16
R lentiform nucleus (putamen)**	24	0	−3	6.47
L dorsolateral prefrontal cortex (BA 9/10)	−30	60	21	6.12
R thalamus (pulvinar)	15	−12	12	5.23
R anterior cingulate cortex (BA 32)*	15	36	18	4.86
Nonscientific circuits > control circuits				
L lingual/parahippocampal gyrus	30	−48	6	5.42
Scientific circuits > control circuits				
No significant activations				

Note. $p < .001$, uncorrected, minimum 10 voxels (except for *: minimum 6 voxels), second-level analysis (random effect analysis, t-test), MNI coordinates in mm, L = left, R = right. ** $p < .0005$, minimum 10 voxels.

error detection mechanisms supports the idea that brain areas involved in error detection may not increase their activity because the task requires both inhibition and error detection.

Another observation strongly supports the idea that activations found in experts' brains during the evaluation of nonscientific circuits are due not only to error detection mechanisms but also to inhibition: the VLPC, the DLPC, and the ACC remain significantly more activated for experts than novices, even when data are merged for both nonscientific and scientific circuits. Since the ratio of circuits judged correct and incorrect becomes equivalent between experts and novices when we merge both conditions, the activation of inhibition-related areas cannot be caused uniquely by the difference in error detection mechanisms, which reinforces the interpretation that experts may need to inhibit a misconception in order to respond correctly.

Reaction Time and Other Brain Areas Related to Scientific Expertise

A limitation to the inhibition hypothesis is that it is not supported by the behavioral data. Indeed, reaction time was significantly lower for experts than novices for all three conditions, suggesting that scientific expertise is related to an increased efficiency for analyzing this kind of visual stimuli and judging their correctness. Usually, inhibition is associated with longer reaction time (Babai, Eidelman, & Stavy, 2012). In this experiment, we did not observe a longer reaction time for experts (although neuroimaging data suggest that experts are inhibiting a misconception), probably because of this increased efficiency. Also, there was no difference in reaction time between conditions for experts. Since we could expect a longer reaction time for circuits that require inhibition (i.e., nonscientific and possibly scientific circuits) than for control circuits, these results support the idea that visual processing related to control circuits, which have a small cut in a wire somewhere in the circuit, takes longer. To avoid this limitation, in further studies, control circuits should be more similar to nonscientific and scientific circuits and should not include a broken wire. For novices, there was no difference in reaction time between nonscientific and scientific circuits. However, answering for both nonscientific and scientific circuits takes significantly more time than for control circuits. This suggests that, although novices are not able to inhibit their misconceptions, they are more hesitant to respond to scientific and nonscientific circuits than to control circuits.

In addition to the frontal regions associated with inhibition, experts, more than novices, activate the right angular gyrus/middle temporal gyrus (BA 39) when evaluating nonscientific and scientific circuits. This brain area, not related to inhibition, is situated at the junction of the occipital, parietal, and temporal lobes, and might be important for linking information coming from these different parts of the brain. The right temporoparietal region (which includes the angular gyrus) plays a role in the attribution of beliefs or intentions to others (Saxe, Whitfield-Gabrieli, Scholz, & Pelphrey, 2009), in shifting attention (Mitchell, 2007), and in the feeling of being outside one's own body (Blanke et al., 2005). In all cases, the activation of the temporoparietal region seems to be associated with a shift in attention from external stimuli to a process of internal reflection. In our study, it is possible that greater activation of the right angular gyrus allows experts to effectively combine visuospatial information, related to electric circuits, with "internal" information probably encoded in the parietal or temporal lobe, and perhaps related to anterior scientific knowledge.

As expected, experts, more than novices, do not activate the brain network involved in inhibition when they evaluate control circuits that are not related to the misconception "one wire can light a bulb." However, we observe a significantly greater activation in the right angular gyrus/middle temporal gyrus (BA 39). Since this brain area is also more activated for nonscientific and scientific circuits, this could mean that this area may be related to scientific expertise, whether or not inhibition is required. It is interesting to note that the activation of the left angular gyrus is significantly correlated with mathematical expertise (Grabner et al., 2007).

Consequences for Conceptual Change and Scientific Teaching

If experts still have a misconception in their brains' neural networks that must be inhibited in order to answer correctly, what does this mean for our understanding of conceptual change and scientific teaching?

As we discussed in the introduction of this article, a number of conceptual change models assume that learners' initial knowledge structures are radically restructured after a conceptual change (Carey, 2009; Chi, 1994; Duit & Treagust, 2003; Giordan & DeVecchi, 1987; Nussbaum & Novick, 1982; Posner et al., 1982; Smith, 2007; Vosniadou, 1994). If the inhibition hypothesis proposed in this article is correct, it could represent a challenge for these kinds of models because implicit to the idea of a radical knowledge restructuring is the idea that the previous knowledge structure does not exist anymore after a conceptual change. Indeed, how could it be necessary to inhibit a misconception if it no longer exists?

To be compatible with the inhibition hypothesis, these models might have to consider the role of intuitions and heuristics that seem to continue to bias the brain, even after a conceptual change has occurred. For example, Vosniadou's model (1994) could take into account that epistemological and ontological presuppositions supporting students' misconceptions persist in learners' minds and are continuously competing with newly accepted presuppositions. Similarly, Chi's model (1994) could consider that initial ontological categorization remains more intuitive than categorization resulting from a conceptual change. Consequently, the tendency to intuitively categorize science concepts may need to be inhibited in order to favor a more scientific and counterintuitive categorization.

Although the inhibition hypothesis might present a challenge for the conceptual change models discussed above, it is, however, consistent with at least two groups of conceptual change models. The first group's models suppose a coexistence of more than one knowledge structure in learners' minds. Mortimer's conceptual change model (1995), Solomon's multiple knowledge system model (1983, 1984) and Bélanger's multilevel of complexity model (2008) belong to this first group. In these models, there is constant competition between coexisting knowledge structures, and inappropriate structures might therefore be controlled or inhibited in order to let the appropriate structure prevail.

The second group includes models proposing that misconceptions are not caused by an underlying knowledge structure, but by intuitive and spontaneous mechanisms of interpretation and decision making (Brown, 1993; diSessa, 1993; Stavy et al., 2006). According to the second group's models, these mechanisms may be systematically influenced by intuition or, more specifically, by fundamental cognitive structures or heuristics that drive the reasoning process in a particular direction, resulting in recurrent erroneous responses. In this perspective, misconceptions are difficult to change because the core cognitive structures that caused them may not be erased from the brain after a conceptual change (probably because they are still useful and reinforced in other contexts). These fundamental cognitive structures that influence the reasoning process have received different names in science education literature. For instance, diSessa (1993) called them "phenomenological primitives," whereas Stavy and Tirosh (2000) used the term "intuitive rules," and Brown (1993) used the name "core intuitions." Following a conceptual change, these fundamental cognitive structures may still exist in learners' brains and may continue to affect decision making, but they may be used in a different way or they may be linked to other cognitive structures (diSessa's model [1993] provides clues as to how this process may occur). In this second group of conceptual change models, experts may require inhibition in order to answer scientifically, not only because the core cognitive structures of intuition still exist after a conceptual change, but also because there is a persistent tendency to use these core cognitive structures in a particular way, which may cause misconceptions to persist.

Although the objective of this study was not to provide direct insights for science teachers, the idea that misconceptions (or the intuitions causing them) are not erased or replaced after a conceptual change has interesting consequences for science education. First, there are studies showing that when students are warned about a potential bias they have to overcome, and when they are trained to identify the responses that seem correct but are, in fact, inappropriate for a particular task, they are more likely to inhibit their incorrect strategies or intuitions (Houdé et al., 2000; Houdé et al., 2001). This teaching strategy (which consists of warnings and training to identify incorrect intuitive responses) might be useful for science teachers. Second, since misconceptions perhaps never disappear, science teachers should never stop discussing misconceptions. In fact, it is usually recommended that teachers confront students' misconceptions at the beginning of a teaching sequence (Kang, Scharmann, Kang, & Noh, 2010; Limón, 2001), but since our results support the idea that misconceptions probably never disappear and may resurface at any time, science teachers should constantly conduct activities involving both misconceptions and scientific knowledge throughout the scientific curriculum, and not only at the beginning of the teaching sequence.

Limitations and Future Directions

This experiment presents some limitations. First, participants were only men, and therefore results cannot be generalized to all students. We rejected women volunteers to reduce the possibility of inter-subject variability that could reduce the statistical power of the analysis. Further studies might focus only on women, or include both women and men, but this last possibility would require more subjects in order to ensure sufficient statistical power. Second, experts in this study were undergraduate students in physics. They may have reached a higher level of scientific expertise than humanities students, but they are still students. Consequently, inhibition might not be necessary for more advanced science students or scientific researchers. Studies comparing graduate science students or scientific researchers with novices will be necessary to know if inhibition plays a temporary or a permanent role in scientific expertise. Third, based on this experiment, we cannot state that the differences observed between novices and experts are due solely to science education because novices and experts may differ in many other ways, not just in terms of their respective educations. They might not have, for example, the same personality, socioeconomic status, or intelligence. To overcome this limitation, further studies should control more variables when selecting participants, or they should study the effects of science education on the brain more directly by comparing brain activations before and after a scientific training session. Fourth, to distinguish more clearly the relative contribution of error detection and inhibition mechanisms (see discussion in the Brain Areas Related to Scientific Expertise and Inhibition section), further studies should add a fourth condition to the task, that is, a condition where both experts and novices respond that electric circuits are correct, but where there is no inhibition necessary to answer correctly. This would allow comparisons of two conditions with the same type of answers (correct in both conditions), but where one requires inhibition in order to answer correctly and the other does not. Another possibility could be to use a block design (instead of an event-related design) in which inhibition and noninhibition blocks include both correct and incorrect electric circuits. Fifth, since the control circuits we used in the task have a wire with a small cut that might induce the need for longer visual processing than other types of electric circuits, behavioral data in this experiment cannot be used flawlessly to support or reject the inhibition hypothesis. In further studies, circuits with a broken wire should not be used as control stimuli.

CONCLUSION

Research in science education has revealed that students often have misconceptions about how nature works that may interfere with learning scientific concepts. However, what happens to these misconceptions after a conceptual change is still an open question. The present fMRI study shows that experts in electricity, more than novices, rely on brain areas related to inhibition when they evaluate the correctness of nonscientific electric circuits. This could mean that experts still have a misconception in their brains' neural networks that must be inhibited to answer scientifically.

The concept of inhibition has not been discussed frequently in the field of science education research, and yet it could considerably change how we regard the learning and teaching of science. From this perspective, learning science is neither about rejecting or replacing misconceptions, nor about simply acquiring new knowledge; it is about controlling and inhibiting a spontaneous tendency that the human brain seems to have for nonscientific explanations.

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REFERENCES

Aron, A. R., Robbins, T. W., & Poldrack, R. A. (2004). Inhibition and the right inferior frontal cortex. *Trends in Cognitive Science*, *8*, 170–177. doi:10.1016/j.tics.2004.02.010

Ashburner, J., & Friston, K. J. (2005). Unified segmentation. *NeuroImage*, *26*, 839–851. doi:10.1016/j.neuroimage.2005.02.018

Babai, R., & Amsterdamer, A. (2008). The persistence of solid and liquid naive conceptions: A reaction time study. *Journal of Science Education and Technology*, *17*, 553–559. doi:10.1007/s10956-008-9122-6

Babai, R., Eidelman, R., & Stavy, R. (2012). Preactivation of inhibitory control mechanisms hinders intuitive reasoning. *International Journal of Science and Mathematics Education*, *10*, 763–775. doi:10.1007/s10763-011-9287-y

Bachelard, G. (1938). *La formation de l'esprit scientifique*. Paris, France: Vrin.

Bandettini, P. A., & Cox, R. W. (2000). Event-related fMRI contrast when using constant interstimulus interval: Theory and experiment. *Magnetic Resonance in Medicine*, *43*, 540–548.

Bélanger, M.. (2008). *Du changement conceptuel à la complexification conceptuelle dans l'apprentissage des sciences* (Unpublished doctoral dissertation). Université de Montréal, Canada.

Blanke, O., Mohr, C., Michel, C. M., Pascual-Leone, A., Brugger, P., Seeck, M., ... Thut, G. (2005). Linking out-of-body experience and self processing to mental own-body imagery at the temporoparietal junction. *The Journal of Neuroscience*, *25*, 550–557. doi:10.1523/JNEUROSCI.2612-04.2005

Botvinick, M. M. (2007). Conflict monitoring and decision making: Reconciling two perspectives on anterior cingulate function. *Cognitive, Affective, and Behavior Neuroscience*, *7*, 356–366.

Brown, D. E. (1993). Refocusing core intuitions: A concretizing role for analogy in conceptual change. *Journal of Research in Science Teaching*, *20*, 1273–1290.

Buckner, R. L. (1998). Event-related fMRI and the hemodynamic response. *Human Brain Mapping*, *6*, 373–377.

Bush, G., Whalen, P. J., Rosen, B. R., Jenike, M. A., McInerney, S. C., & Rauch, S. L. (1998). The counting stroop: An interference task specialized for functional neuroimaging–validation study with functional MRI. *Human Brain Mapping*, *6*, 270–282.

Carey, S. (2009). *The origin of concepts*. New York, NY: Oxford University Press.

Çepni, S., & Keleş, E. (2006). Turkish students' conceptions about the simple electric circuits. *International Journal of Science and Mathematics Education*, *4*, 269–291.

Chen, C.-Y., Muggleton, N. G., Tzeng, O. J. L., Hung, D. L., & Juan, C.-H. (2009). Control of prepotent responses by the superior medial frontal cortex. *NeuroImage*, *44*, 537–545.

Chi, M. T. H. (1994). From things to processes: A theory of conceptual change for learning science concepts. *Learning and Instruction*, *4*, 27–43.

De Neys, W., Vartanian, O., & Goel, V. (2008). Smarter than we think: When our brains detect that we are biased. *Psychological Science*, *19*, 483–489. doi:10.1111/j.1467-9280.2008.02113.x

Duit, R., & Treagust, D. F. (2003). Conceptual change: A powerful framework for improving science teaching and learning. *International Journal of Science Education*, *25*, 671–688.

Duit, R., & Treagust, D. F. (2012). How can conceptual change contribute to theory and practice in science education? In B. J. Fraser, K. Tobin & C. J. McRobbie (Eds.), *Second international handbook of science education* (pp. 107–118). Dordrecht, The Netherlands: Springer.

Dunbar, K. N., Fugelsang, J. A., & Stein, C. (2007). Do naïve theories ever go away? Using brain and behavior to understand changes in concepts. In M. C. Lovett & P. Shah (Eds.), *Thinking with data: 33rd Carnegie symposium on cognition* (pp. 193–206). Mahwah, NJ: Lawrence Erlbaum.

Friston, K. J., Williams, S., Howard, R., Frackowiak, R. S. J., & Turner, R. (1996). Movement-related effects in fMRI time-series. *Magnetic Resonance in Medicine*, *35*, 346–355.

Giordan, A., & DeVecchi, G. (1987). *Les origines du savoir*. Neuchatel, Switzerland: Delachaux.

Goldberg, R. F., & Thompson-Schill, S. L. (2009). Developmental "roots" in mature biological knowledge. *Psychological Science*, *20*, 480–487. doi:10.1111/j.1467-9280.2009.02320.x

Grabner, R. H., Ansari, D., Reishofer, G., Stern, E., Ebner, F., & Neuper, C. (2007). Individual differences in mathematical competence predict parietal brain activation during mental calculation. *NeuroImage*, *38*, 346–356. doi:10.1016/j.neuroimage.2007.07.041

Houdé, O., Zago, L., Crivello, F., Moutier, S., Pineau, A., Mazoyer, B., & Tzourio-Mazoyer, N. (2001). Access to deductive logic depends on a right ventromedial prefrontal area devoted to emotion and feeling: Evidence from a training paradigm. *NeuroImage*, *14*, 1486–1492.

Houdé, O., Zago, L., Mellet, E., Moutier, S., Pineau, A., Mazoyer, B., & Tzourio-Mazoyer, N. (2000). Shifting from the perceptual brain to the logical brain: The neural impact of cognitive inhibition training. *Journal of Cognitive Neuroscience*, *12*, 721–728.

Kang, H., Scharmann, L. C., Kang, S., & Noh, T. (2010). Cognitive conflict and situational interest as factors influencing conceptual change. *International Journal of Environmental and Science Education*, *5*, 383–405.

Kelemen, D., Rottman, J., & Seston, R. (2012). Professional physical scientists display tenacious teleological tendencies: Purpose-based reasoning as a cognitive default. *Journal of Experimental Psychology: General*, *142*, 1074–1083. doi:10.1037/a0030399

Kwon, Y.-J., & Lawson, A. E. (2000). Linking brain growth with the development of scientific reasoning ability and conceptual change during adolescence. *Journal of Research in Science Teaching*, *37*, 44–62.

Liddle, P. F., Kiehl, K. A., & Smith, A. M. (2001). Event-related fMRI study of response inhibition. *Human Brain Mapping*, *12*, 100–109.

Limón, M. (2001). On the cognitive conflict as an instructional strategy for conceptual change: A critical appraisal. *Learning and Instruction*, *11*, 357–380. doi:10.1016/s0959-4752(00)00037-2

Liu, X. (2001). Synthesizing research on student conceptions in science. *International Journal of Science Education*, *23*, 55–81. doi:10.1080/09500690119778

Lombrozo, T., Kelemen, D., & Zaitchik, D. (2007). Inferring design: Evidence of a preference for teleological explanations in patients with Alzheimer's disease. *Psychological Science*, *18*, 999–1006. doi:10.1111/j.1467-9280.2007.02015.x

MacDonald, A. W. (2000). Dissociating the role of the dorsolateral prefrontal and anterior cingulate cortex in cognitive control. *Science*, *288*, 1835–1838. doi:10.1126/science.288.5472.1835

Masson, S., Potvin, P., Riopel, M., Brault Foisy, L.-M., & Lafortune, S. (2012). Using fMRI to study conceptual change: Why and how? *International Journal of Environmental and Science Education*, *7*, 19–35.

Menon, V., Adleman, N. E., White, C. D., Glover, G. H., & Reiss, A. L. (2001). Error-related brain activation during a Go/NoGo response inhibition task. *Human Brain Mapping*, *12*, 131–143.

Mitchell, J. P. (2007). Activity in right temporo-parietal junction is not selective for theory-of-mind. *Cerebral cortex*, *18*, 262–271. doi:10.1093/cercor/bhm051

Monchi, O., Petrides, M., Petre, V., Worsley, K., & Dagher, A. (2001). Wisconsin card sorting revisited: Distinct neural circuits participating in different stages of the task identified by event-related functional magnetic resonance imaging. *Journal of Neuroscience*, *21*, 7733–7741.

Mortimer, E. F. (1995). Conceptual change or conceptual profile change? *Science and Education*, *4*, 267–285. doi:10.1007/bf00486624

Nathaniel-James, D. A., Fletcher, P., & Frith, C. D. (1997). The functional anatomy of verbal initiation and suppression using the Hayling Test. *Neuropsychologia*, *35*, 559–566. doi:10.1016/S0028-3932(96)00104-2

Nussbaum, J., & Novick, S. (1982). Alternative frameworks, conceptual conflict and accommodation: Toward a principled teaching strategy. *Instructional Science*, *11*, 183–200.

Periago, M. C., & Bohigas, X. (2005). A study of second-year engineering students' alternative conceptions about electric potential, current intensity and Ohm's law. *European Journal of Engineering Education*, *30*, 71–80.

Posner, G. J., Strike, K. A., Hewson, P. W., & Gertzog, W. A. (1982). Accommodation of a scientific conception: Toward a theory of conceptual change. *Science Education*, *66*, 211–227.

Rubia, K., Russell, T., Overmeyer, S., Brammer, M. J., Bullmore, E. T., Sharma, T., ... Taylor, E. (2001). Mapping motor inhibition: Conjunctive brain activations across different versions of go/no-go and stop tasks. *NeuroImage*, *13*, 250–261. doi:10.1006/nimg.2000.0685

Saxe, R. R., Whitfield-Gabrieli, S., Scholz, J., & Pelphrey, K. A. (2009). Brain regions for perceiving and reasoning about other people in school-aged children. *Child Development*, *80*, 1197–1209. doi:10.1111/j.1467-8624.2009.01325.x

diSessa, A. A. (1993). Toward an epistemology of physics. *Cognition and Instruction*, *10*, 105–225.

diSessa, A. A. (2006). A history of conceptual change research: Threads and fault lines. In R. K. Sawyer (Ed.), *Cambridge handbook of the learning sciences* (pp. 265–281). Cambridge, UK: Cambridge University Press.

Shtulman, A., & Valcarcel, J. (2012). Scientific knowledge suppresses but does not supplant earlier intuitions. *Cognition*, *124*, 209–215. doi:10.1016/j.cognition.2012.04.005

Smith, C. L. (2007). Bootstrapping processes in the development of students' commonsense matter theories: Using analogical mappings, thought experiments, and learning to measure to promote conceptual restructuring. *Cognition and Instruction*, *25*, 337–398. doi:10.1080/07370000701632363

Solomon, J. (1983). Learning about energy: How pupils think in two domains. *European Journal of Science Education*, *5*, 49–59.

Solomon, J. (1984). Prompts, cues and discrimination: The utilization of two separate knowledge systems. *European Journal of Science Education*, *6*, 277–284.

Stavy, R., Babai, R., Tsamir, P., Tirosh, D., Lin, F.-L., & McRobbie, C. (2006). Are intuitive rules universal? *International Journal of Science and Mathematics Education*, *4*, 417–436.

Stavy, R., & Tirosh, D., (2000). How students (mis-)understand science and mathematics: Intuitive rules. New York, NY: Teachers College Press.

Vosniadou, S. (1994). Capturing and modeling the process of conceptual change. *Learning and Instruction*, *4*, 45–69. doi:10.1016/0959-4752(94)90018-3

Vosniadou, S. (2008). Conceptual change research: An introduction. In S. Vosniadou (Ed.), *International handbook of research on conceptual change* (pp. xiii–xxviii). New York, NY: Routledge.

Vosniadou, S. (2012). Reframing the classical approach to conceptual change: Preconceptions, misconceptions and synthetic models. In B. J. Fraser, K. Tobin, & C. J. McRobbie (Eds.), *Second international handbook of science education* (pp. 119–130). Dordrecht, The Netherlands: Springer.

Wandersee, J. H., Mintzes, J. J., & Novak, J. D. (1994). Research on alternative conceptions in science. In D. L. Gabel (Ed.), *Handbook of research on science teaching and learning* (pp. 177–210). New York, NY: Macmillan.

Zaitchik, D., & Solomon, G. E. (2008). Animist thinking in the elderly and in patients with Alzheimer's disease. *Cognitive Neuropsychology*, *25*, 27–37. doi:10.1080/02643290801904059