Understanding Conceptual Change and Science Learning through Educational Neuroscience

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ABSTRACT— Although the field of educational neuroscience has grown in recent years, little research has been conducted on conceptual change and science learning through an educational neuroscience framework. Educational neuroscience is frequently used to study processes of language and mathematics cognition, but is not extensively applied to conceptual change and science learning. This review integrates insights from extant conceptual change educational neuroscience studies to inform the fields of educational psychology and science education. These new insights shed light on the persistence of misconceptions and the roles of error detection, inhibition, executive function, and memory in conceptual change. Future directions for the study of conceptual change and educational neuroscience are discussed.

In the past two decades, there has been a growing body of educational neuroscience research (Masson, Potvin, Riopel, Brault Foisy, & Lafortune, 2012; Szucs & Goswami, 2007; Willingham & Lloyd, 2007) focused on a wide range of topics, including how knowledge is represented and how changes to this knowledge are reflected within the mind (Petitto & Dunbar, 2004). While educational neuroscience, and more specifically brain imaging methodologies, are extensively employed to study language and mathematics cognition, the same cannot be said for conceptual change and science learning.

In this commentary, we relate literature from behavioral studies on conceptual change and science learning from the field of educational psychology to results from studies using neuroscience research methods to investigate which brain regions and their associated cognitive processes are recruited to perform specific science-related tasks. We conclude by discussing the implications of such discoveries for refining theories of conceptual change, as well as considerations for future research.

BEHAVIORAL RESEARCH ON CONCEPTUAL CHANGE AND SCIENCE LEARNING

Conceptual change is especially important and relevant to science learning (Sinatra, Kienhues, & Hofer, 2014). Science learning involves the acquisition, understanding, and alteration of scientifically appropriate conceptions. More specifically, science learning often necessitates the use and manipulation of concepts (i.e., categorical representations of similar ideas, objects, or events) as well as individual items from procedural memory (i.e., unconsciously recalled skills, tacit rules, habits, and other conditioned emotional or cognitive effects, including priming) and declarative memory (i.e., consciously recalled facts or experienced events). Whereas the acquisition of procedural knowledge may involve gaining practice at carrying out steps in a protocol and the acquisition of declarative knowledge may involve memorizing dates, names, and descriptive facts, conceptual change can be more complex since it may involve altering multiple, interrelated pieces of procedural and declarative knowledge (de Jong & Ferguson, 1996; Farnham-Diggory, 1994). For example, *stating* that congestion is a symptom of the

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Table 1
Types of Knowledge

Procedural	*Declarative*	*Conceptual*
Knowledge *how*	Knowledge *that*	Knowledge of *structures* and *relationships*
Rules, recipes; meaningful action; action sequences	Words, symbols	Symbols and formulae; propositions; concepts and relations; categories and schemata
Isolated processes; actions related to concept	Knowledge of formal language or symbolic representations	Independent concepts and laws; meaningful and hierarchical structure
Application	Compilation	Relation
Unconscious recall	Conscious recall	
Covering one's face when coughing or sneezing	Common cold is caused by a virus	Common cold is caused by a virus that can be spread through coughing and sneezing

Note: de Jong and Ferguson (1996), Farnham-Diggory (1994), Peterson, Ridenour, and Somers (1990).

common cold is declarative knowledge; *knowing how* to thoroughly wash one's hands to minimize catching the common cold is procedural knowledge; yet, *understanding* the common cold as a concept involves integrating related facts, ideas, and processes. For example, one's concept of the common cold might include that it is caused by a virus, predominantly resides in one's nasal cavity, can be prevented through hand washing and cannot be cured by taking antibiotics. A misconception might include that the common cold is caused by going outside in cold weather. Table 1 differentiates these types of knowledge.

Concepts are difficult to change or correct when learners hold misconceptions (Dole & Sinatra, 1998; Nadelson, Heddy, Jones, Taasoobshirazi, & Johnson, 2018). The difficulty in achieving conceptual change is, in part, due to interrelationships among various pieces of knowledge (DiSessa, 2008); therefore, it may require overhauling a substantial amount of information. Additionally, there may be psychosocial factors that work against conceptual change, such as being emotionally invested in a misconception, not seeing any flaws or not being motivated to discard a held misconception, cultural-environmental expectations to hold onto a misconception, or not believing that the source of new information is credible (Sinatra & Seyranian, 2015).

Conceptual change is theorized to be more apt to occur when a scientific viewpoint is offered, possibly sparking cognitive conflict, a type of error detection, within those who hold misconceptions (Broughton, Sinatra, & Reynolds, 2010; Limón, 2001; Posner, Strike, Hewson, & Gertzog, 1982). Educational psychologists have found that activating background knowledge, participating in supplemental science investigations, promoting adaptive psychosocial constructs (i.e., utility values), and reading refutation texts (i.e., a text which directly counters a known misconception) are the among most effective interventions for promoting conceptual change (Broughton et al., 2010; Diakidoy, Kendeou, & Ioannides, 2003; Guzzetti, Snyder, & Glass, 1992; Hesse-Biber & Johnson, 2013; Johnson & Sinatra, 2013; Vaughn & Johnson, 2018).

Posner et al. (1982) proposed an early theory of conceptual change, describing the processes of assimilating or accommodating new information with a learner's previous concepts; and hypothesized that, for conceptual change to occur, learners must become dissatisfied with their existing conception, and find the new conception to be intelligible, plausible, and fruitful. A decade following their initial theory, Strike and Posner (1992) expressed the need to revise their theory of conceptual change due to its lack of accounting for learners' attitudes, emotions, and motivation. Pintrich, Smith, Garcia, and Mckeachie (1993) referred to earlier perspectives of conceptual change as being "cold," due to their focus on rational, cognitive factors, and not taking into account "hotter" (i.e., human) constructs. A "warming trend" in conceptual change theory saw the addition of affective variables, such as engagement, motivation, and threat to self (Sinatra, 2005). Although both the cognitive reconstruction of knowledge model (CRKM; Dole & Sinatra, 1998) and the more contemporary dynamic model of conceptual change (Nadelson et al., 2018) include "cold" and "hot" factors in the conceptual change process, no conceptual change model, to the best of our knowledge, addresses the neural processes involved in conceptual change and the insights educational neuroscience might provide for the field.

While there is ample research on conceptual change and science learning within educational psychology, integration with neuroscientific research has not yet occurred. In this commentary, we review studies that have investigated brain regions and networks involved in science learning and knowledge revision (Brault Foisy, Potvin, Riopel, & Masson, 2015; Dunbar, Fugelsang, & Stein, 2007; Fugelsang & Dunbar, 2005; Masson et al., 2012; Masson, Potvin, Riopel, & Brault Foisy, 2014; Potvin, Turmel, & Masson, 2014) with the goal of addressing some of the lingering questions in conceptual change research regarding mechanisms of assimilation and accommodation (e.g., Palmer, 2003) and conceptual prevalence and resubsumption (Ohlsson, 2009). Furthermore, neuroscience research may provide insight into current models of conceptual change, such as the CRKM (Dole & Sinatra, 1998), knowledge revision components framework (Kendeou & O'Brien, 2014; Kendeou, Walsh, Smith, & O'Brien, 2014), plausibility judgments in conceptual change model (Lombardi, Nussbaum, & Sinatra, 2016), and the cognitive-affective model of conceptual change (Gregoire, 2003).

NEUROSCIENCE RESEARCH ON CONCEPTUAL CHANGE AND SCIENCE LEARNING

Over the past two decades, neuroscience research has proliferated. The field's research methods provide us with tools for discovering how knowledge, thought, and learning are embodied in our brains through neural activity. Innovations in neuroimaging technologies, such as functional magnetic resonance imaging (fMRI) and event-related potentials (ERP), allow us to visualize the neural activity associated with specific cognitive processes through blood flow (e.g., fMRI) and electrical (e.g., ERP) changes in the brain (for a review, see Brown, 2018). Related to these developments, an educational neuroscience framework has emerged that creates opportunities for interdisciplinary, translational research relating multiple levels of analysis, including brain structures, cognitive functions, behavior, and educational interventions (e.g., Brown & Bjorklund, 1998; Brown & Chiu, 2006; Byrnes & Fox, 1998; Coch, Michlovitz, Ansari, & Baird, 2009; Goswami, 2006; Hille, 2011; Johnson, Halit, Grice, & Karmiloff-Smith, 2002; Magill-Evans, Hodge, & Darrah, 2002; Mareschal, Butterworth, & Tolmie, 2013; Varma, McCandliss, & Schwartz, 2008). As noted by Katzir and Paré-Blagoev (2006), "Brain research can challenge common-sense views about teaching and learning by suggesting additional systems that are involved in particular tasks and activities" (p. 70). However, educational psychologists have justifiably expressed concerns regarding the value and interpretations of some neuroscience research, noting counterproductive misapplications (e.g., Alferink & Farmer-Dougan, 2010; Bowers, 2016; Bruer, 1997; Crone, Poldrack, & Durston, 2010; Geake, 2008; Goswami, 2006; Howard-Jones, 2014; Lindell & Kidd, 2011; Turner, 2014). However, we find it productive to consider some questions related to conceptual change and science learning using an educational neuroscience framework, such as "Why are some scientific concepts so difficult to learn?" and "Why are common science misconceptions so difficult to ameliorate?" Understanding how knowledge and changes to knowledge are reflected in the brain can help inform this inquiry. Exploration of the neural substrate of knowledge change can explore both the "colder" and "warmer" models of conceptual change described earlier. While educational neuroscience research in this area remains nascent, the following studies shed light on the brain regions and networks involved in science learning and knowledge revision. Table 2 summarizes the results for the literature reviewed for each major brain area.

In an fMRI study, Fugelsang and Dunbar (2005) investigated complex causal thinking. Participants were given one of two introductory statements regarding the mechanism of an antidepressant: a direct *plausible* causal mechanism of action, or no direct causal mechanism. While brain activation was measured, participants were shown data that were either *consistent* or *inconsistent* with these mechanisms. The researchers found that during the evaluation of a *plausible* theory, activation was found in the right superior frontal gyrus and left inferior frontal gyrus, areas associated with working memory and executive function, as well as portions of the primary visual cortex associated with visual attention. When data *consistent* with a theory were presented, regions associated with learning and memory, such as the caudate and parahippocampal gyrus, were activated. When data *inconsistent* with a theory were presented, areas associated with error detection, conflict monitoring and inhibition, including the left dorsolateral prefrontal cortex [DL-PFC]) and dorsal regions of the anterior cingulate cortex [ACC]) were activated. Interestingly, the precuneus was activated, which the authors attributed to reallocation of attentional resources, but has also been associated with a variety of "highly integrated tasks, including visuo-spatial imagery, episodic memory retrieval and self-processing operations, namely first-person perspective taking and an experience of agency" (Cavanna & Trimble, 2006, p. 564). The authors suggested that this finding may reflect confirmatory or other types of belief bias effects.

Dunbar et al. (2007) describe a follow-up, pilot study in which they compared participants who were physics experts (at least five college courses) to novices (no high school or college physics courses) to investigate major conceptual change. They chose to examine brain activity related to conceptions of Newtonian physics (i.e., balls should fall at the same rate in a frictionless environment) because many people hold erroneous beliefs (i.e., Impetus theories) and conceptual shifts to Newtonian theories occur only after extensive learning. Students were shown videos of two balls falling at the same rate or at a different rate and asked to press keys indicating that a ball *should* or *should not* fall this way in a frictionless environment. For some videos, the two balls were the same size, for other videos one ball was big and the other was small. The participants were similar, including equal gender distribution, age, and SAT scores. The authors reported increased activation within the ACC relative to baseline, which is associated with error detection, when physics *experts* viewed *incorrect* examples (e.g., a bigger ball falling faster than a smaller ball) and when *novices* viewed scientifically *correct*, but nonintuitive, examples (e.g.,

Table 2
Regions and Proposed Cognitive Processes Showing Greater Activation for Specific Science-Related Tasks for Each Major Brain Area for Literature Reviewed

Citation		*Fugelsang and Dunbar (2005), Dunbar et al. (2007)*	*Masson et al. (2014)*	*Potvin et al. (2014)*	*Brault Foisy et al. (2015)*
Regions Activated	*Proposed Cognitive Processes*	*Specific Science-Related Tasks*			
Frontal lobe					
Anterior prefrontal cortex (BA 10) Dorsolateral prefrontal cortex (BA 9/46/8)	Working memory Executive function Error detection Conflict monitoring Inhibition Uncertainty	Evaluating a *plausible* vs. implausible theory Viewing data *consistent* or *inconsistent* with a *plausible* theory	*Experts* vs. novices while evaluating *incorrect* circuits *Novices* while evaluating *correct* vs. circuits	*Novices* selecting *uncertain* answers while evaluating electric circuits	*Experts* vs. novices while evaluating scientifically *incorrect* stimuli *Novices* while evaluating scientifically *incorrect* vs. correct stimuli
Inferior frontal gyrus Ventrolateral prefrontal cortex (BA 44/45/47)	Working memory Executive function Inhibition	Evaluating a *plausible* theory	*Experts* vs. novices while evaluating *incorrect* circuits	*Novices* selecting *certain* and *uncertain* answers while evaluating electric circuits	*Experts* vs. novices while evaluating scientifically *incorrect* stimuli *Novices* while evaluating scientifically *incorrect* vs. correct stimuli
Precentral gyrus Premotor/ supplementary motor area (BA 4/6)	Allocating visual attention	Viewing data *consistent* with a theory		*Novices* selecting *certain* answers while evaluating electric circuits *Novices* selecting *certain* answers while identifying *correct* and *incorrect* electric circuits	*Novices* vs. experts while evaluating scientifically *correct* stimuli *Experts* while evaluating scientifically *incorrect* vs. control stimuli

Table 2
continued

Citation		*Fugelsang and Dunbar (2005), Dunbar et al. (2007)*	*Masson et al. (2014)*	*Potvin et al. (2014)*	*Brault Foisy et al. (2015)*
Regions Activated	*Proposed Cognitive Processes*	*Specific Science-Related Tasks*			
Temporal lobe					
Middle/superior temporal gyrus and pole (BA 21/22/38)	Language processing Declarative and semantic memory			*Novices* selecting *uncertain* answers while evaluating electric circuits	
Inferior temporal gyrus	Allocating visual attention			*Novices* selecting *certain* answers while evaluating electric circuits	
Fusiform gyrus (BA 37)	Visuospatial processing			*Novices* selecting *certain* answers while identifying *correct* electric circuits	
Parietal lobe					
Postcentral gyrus (BA 2/3)	Proprioception Integration of somatosensory stimuli Memory formation			*Novices* selecting *certain* answers while evaluating electric circuits *Novices* selecting *certain* answers while identifying *correct* and *incorrect* electric circuits	*Novices* while evaluating scientifically *incorrect* vs. correct and control stimuli
Superior parietal lobe Precuneus (BA 7)	Error detection Conflict monitoring Reallocation of attentional resources Visuospatial processing	Viewing data *consistent* or with a theory Viewing data *inconsistent* with a *plausible* theory	*Experts* while evaluating *incorrect* vs. correct circuits	*Novices* selecting *certain* answers while evaluating electric circuits	*Experts* while evaluating scientifically *incorrect* vs. correct stimuli

Table 2
continued

Citation		*Fugelsang and Dunbar (2005), Dunbar et al. (2007)*	*Masson et al. (2014)*	*Potvin et al. (2014)*	*Brault Foisy et al. (2015)*
Regions Activated	*Proposed Cognitive Processes*	*Specific Science-Related Tasks*			
Intraparietal sulcus (BA 7)	Allocating visual attention Visuospatial processing			*Novices* selecting *certain* answers while identifying *correct* electric circuits	
Angular gyrus (BA 39)	Visuospatial processing		*Experts* vs. novices while evaluating *correct*, *incorrect*, and *control circuits*	*Novices* selecting *certain* answers while evaluating electric circuits	
Inferior parietal lobe/lateral sulcus (BA 40)	Visuospatial processing		*Novices* while evaluating *correct* vs. incorrect circuits	*Novices* selecting *certain* answers while evaluating electric circuits	
Occipital lobe					
Primary visual cortex (BA 17) Lingual gyrus (BA 18) Occipito-temporal cortex (BA 19)	Visual attention	Evaluating a *plausible* theory	*Experts* while evaluating *incorrect* vs. correct circuits	*Novices* selecting *certain* answers while evaluating electric circuits	*Experts* while evaluating scientifically *incorrect* vs. correct stimuli
Limbic System					
Anterior cingulate cortex (BA 24/32)	Error detection Conflict monitoring Uncertainty	Viewing data *consistent* with a theory Viewing data *inconsistent* with a *plausible* theory *Experts* viewing *incorrect* mechanics *Novices* viewing *correct*, nonintuitive, mechanics	*Experts* vs. novices while evaluating *incorrect* circuits *Novices* while evaluating *correct* vs. incorrect circuits	*Novices* selecting *uncertain* answers while evaluating electric circuits	*Novices* while evaluating scientifically *incorrect* vs. correct stimuli *Novices* while evaluating *correct* stimuli vs. incorrect stimuli

Table 2
continued

Citation		*Fugelsang and Dunbar (2005), Dunbar et al. (2007)*	*Masson et al. (2014)*	*Potvin et al. (2014)*	*Brault Foisy et al. (2015)*
Regions Activated	*Proposed Cognitive Processes*	*Specific Science-Related Tasks*			
Anterior insula cortex (BA 13)	Uncertainty			Novices selecting *certain* and *uncertain* answers while evaluating electric circuits	
	Emotional awareness				
Caudate	Learning	Viewing data *consistent* with a theory			
	Memory				
R. lentiform nucleus (putamen)	Learning		*Novices* while evaluating *correct* vs. incorrect circuits		
R. thalamus (pulvinar)	Visual attention		*Novices* while evaluating *correct* vs. incorrect circuits		
Parahippocampal gyrus	Learning	Viewing data *consistent* with a theory	*Novices* while evaluating *incorrect* vs. control circuits		
	Contextual, episodic, and spatial memory				

BA = Brodmann area.

a bigger ball falling at the same rate as a smaller ball). They concluded that physics experts may have undergone conceptual change during their studies, which is reflected in their brain activation. Interestingly, Dunbar and colleagues reported that half of the novices correctly judged that the two balls falling at the same rate is natural, but nevertheless still showed relatively greater activation in the ACC when they saw two balls of different mass falling at the same rate. Based on these data, the authors concluded that, despite providing the correct answer behaviorally, the brain imaging data suggest that the novices had not undergone deep conceptual change. The imaging data provide an additional level of understanding that many students can select the correct answer without truly understanding concepts.

Brault Foisy et al. (2015) investigated the misconception that heavier objects will fall faster than lighter objects (as opposed to big vs. small), which they prescreened in participants (all males) who were experts (physics students) who demonstrated that they did not hold this misconception and novices (humanities students) who demonstrated that they held this misconception. Comparing across groups, the researchers found that, when asked to evaluate scientifically *incorrect* stimuli, experts showed significantly greater activation than novices in the left DL-PFC, anterior PFC, and the right VL-PFC, indicating inhibition processes; while novices showed significantly greater activation than experts in the supplementary motor area (SMA) when evaluating the scientifically *correct* stimuli. For scientifically *incorrect* stimuli in comparison to correct stimuli, *experts* showed greater activation in the right premotor area/SMA, right superior parietal lobule, and right lingual gyrus; while *novices* showed greater activation in the left postcentral gyrus, the right DL-PFC and VL-PFC, and in the left ACC. *Novices* also showed greater activation in the right ACC for scientifically *correct* stimuli in comparison to incorrect stimuli. For scientifically *incorrect* stimuli in comparison to control stimuli, *experts* showed greater activation in the right premotor area; whereas novices showed greater activity in the left postcentral gyrus. The researchers concluded that *experts* activate areas of the brain associated with inhibition when they evaluate scientifically *incorrect* stimuli. They suggest that experts' misconceptions have not been eradicated or transformed during learning, but remained encoded and were then inhibited to provide a correct answer.

While the experimental conditions and results differ between Dunbar et al. (2007) and Brault Foisy et al. (2015), the findings provide convergent evidence. When *experts* view *nonscientific*, *incorrect* examples, there is activation in the ACC, associated with error detection; when *experts* view *scientific*, *correct* but *nonintuitive* examples, they show activation in areas associated with inhibition and executive function. *Novices*, on the other hand, show greater activation in the ACC when shown *scientific*, *correct*, but *nonintuitive*, examples.

Masson et al. (2014) used fMRI to compare brain activation between participants (all males) who were science experts (physics students) or novices (humanities students) in evaluating the correctness of simple electric circuits to address whether misconceptions are rejected and replaced by scientific conceptions or still present in students' minds, coexisting with newly acquired scientific conceptions. Questionnaire responses were used to prescreen participants to ensure that most experts did not hold misconceptions and that most novices did. Participants evaluated whether images of three types of electric circuits were correct or incorrect by pressing buttons. *Correct* circuits represented that two wires are needed to light a bulb, *incorrect* circuits represented a misconception that a single wire is sufficient to light a bulb, and *control* circuits presented a broken circuit, which novices and experts were expected to respond to similarly and was not predicted to involve inhibition of a misconception.

Behavioral data revealed that *experts* showed significantly higher levels of accuracy in evaluating scientifically *correct* and *incorrect* circuits in comparison to novices, but there were no differences in performance for *control* circuits, as expected. *Experts* showed significantly faster response times than novices for all types of circuits, but no significant within-subjects differences; whereas, *novices* showed significant differences in response times between the scientifically *correct* and *incorrect* (which were mostly inaccurate responses) circuits and the *control* circuits (which were mostly accurate responses).

Interestingly, brain imaging data for *correct* circuits showed that *experts* activated their right angular gyrus/middle temporal gyrus more than novices; whereas *novices* showed significantly more activation in the left DL-PFC compared to experts. However, when evaluating *incorrect* circuits, *experts* showed greater activation than novices in the left DL-PFC, VL-PFC, right ACC, right angular gyrus/middle temporal gyrus; whereas novices did not activate any brain area significantly more than experts. When assessing the correctness of the *control* circuits, *experts* showed greater activation than novices in the right angular gyrus/middle temporal gyrus; whereas novices did not activate any brain areas significantly more than experts. Within group comparisons revealed that *experts* showed greater activation in the right occipitotemporal cortex and the left superior parietal lobe/precuenus when evaluating the *incorrect* circuits in comparison to the correct circuits. The *novices* showed significantly greater activation in the left DL-PFC and the right ACC for the *correct* circuits in comparison to the incorrect circuits and significantly greater activation in the left lingual/parahippocampal gyrus for the *incorrect* in comparison to the control circuits. These findings support Masson et al. (2014) hypothesis that areas related to inhibition, error detection, and conflict monitoring are activated by scientifically *incorrect* stimuli in experts. The authors concluded that misconceptions may be retained in experts memories and must be inhibited in order for them to provide scientifically correct responses. Thus, although "experts" have successfully learned and applied correct scientific conceptions, when exposed to common misconceptions, brain activity reveals activation in areas associated with inhibition and executive function, suggesting that experts must still suppress prior misconceptions.

Potvin et al. (2014) present a novel approach to the electric circuit fMRI studies. They created a bank of photographic images of series, parallel, and mixed correct and incorrect electric circuits made of real bulbs, wires, and a battery, which were intentionally designed to elicit various levels of certainty and uncertainty in that some were more intuitive and did not involve any known misconceptions, while other were less intuitive and involved well-known misconceptions. Novices (humanities and arts students) were asked to indicate whether or not they thought the light bulbs in images presenting electric circuits would light up correctly by pushing one of four buttons, each corresponding to a different finger and response: (1) "The circuit is correct; I am certain."; (2)"I think the circuit is correct, but I am uncertain."; (3) "The circuit is incorrect; I am certain."; and (4) "I think the circuit is incorrect, but I am uncertain.".

When participants indicated that they were *uncertain* of their answers, four brain areas showed significantly greater activation, including the left middle/superior temporal gyrus, right superior frontal gyrus, bilateral ACC, left inferior frontal gyrus/superior temporal gyrus and insula into the lateral sulcus. When participants indicated that they were *certain* about their answers, they showed a large bilateral pattern of activation from the middle/inferior occipital gyrus and the inferior temporal gyrus to the angular gyrus and superior parietal lobe, which are typically associated with visuospatial processing. Furthermore, there was bilateral activation of the inferior parietal lobule and the postcentral gyrus, as well as activation at the right inferior/middle frontal gyrus, insula, and precentral gyrus. When participants were *certain* and *correct* in comparison to certain and incorrect, five brain areas were significantly more activated including the left and right intraparietal sulcus, the right premotor cortex, the right fusiform gyrus, and the right motor cortex, which are typically associated with allocating visual attention resources. When participants were *certain* and *incorrect* in comparison to certain and correct, they showed greater activation in the left motor cortex. Potvin et al. (2014) suggest that these findings support multiple-choice tasks as complex decision-making processes during which students must monitor, not distinguish, between correct and incorrect answer choices, but also appraise their level of certainty for each answer choice. The authors interpreted their results as supporting conceptual change theories that acknowledge that many conceptions about a single phenomenon can coexist and conflict with one another with modifications in relative statuses at the expense of others until one prevails, in contrast to those that postulate that learning leads to the modification or restructuring of initial conceptions.

CONCLUSION

This commentary provides an initial summary of studies that have examined brain activation and associated cognitive processes hypothesized to be involved in conceptual change for science-related tasks. Our review of this small set of studies illustrates that science learning is complex, involving an orchestration of many brain networks and regions relating a vast array of knowledge and performing a variety of cognitive processes. Although results were found in each of the major brain areas, all studies found significant activation in the DL-PFC, VL-PFC, ACC, superior parietal lobe/precuneus, and visual cortex for science-related tasks, which were attributed to working memory, executive function, error detection, conflict monitoring, inhibition, reallocation of attentional resources, visuospatial processing, and visual attention. This type of information may help educational psychologists address lingering questions in conceptual change research regarding mechanisms of assimilation and accommodation (e.g., Palmer, 2003) and conceptual prevalences and resubsumption (Ohlsson, 2009). Furthermore, it provides insight into current models of conceptual change and may inform educational practice and interventions.

The overarching findings from these studies indicate that conceptual change, even long-term conceptual change found in experts, does not completely ameliorate prior misconceptions. Thus, they collectively support hypotheses of conceptual change frameworks in which misconceptions are not "removed"; instead, misinformation that was encoded into long-term memory must be inhibited and correct conceptions acquired through learning must be retrieved (Nadelson et al., 2018) as evidenced by activation of areas of the PFC associated with inhibition and executive function. Thus, it makes sense for educational interventions to target conflict monitoring and inhibition skills in science learning contexts, specifically when students encounter data that is inconsistent with what they believe. For example, findings from eye tracking and reaction time studies indicate that refutation statements induce cognitive conflict and prepare the reader for scientifically accurate facts to be presented (Ariasi, Hyönä, Kaakinen, & Mason, 2017; Kendeou & Van den Broek, 2007). Many studies in conceptual change rely on participants reading text or otherwise interacting with incorrect and correct concepts. In future research, such studies (e.g., Broughton et al., 2010; Johnson & Sinatra, 2013; Mason et al., 2017; McCrudden & Kendeou, 2014; Vaughn & Johnson, 2018) would be especially well-suited for a preintervention and postintervention fMRI study examining specific regions of interest that gauge error detection (i.e., ACC) to better understand conceptual change and the types of stimuli and instructions that best promote it. As shown in Table 2, allocating visual attention and visuospatial processing are also important components involved in science-related tasks that could be incorporated into intervention activities.

The current review also highlights the involvement of both "cold" (e.g., executive function) and "warmer" (e.g., emotional awareness, uncertainty) processes related to conceptual change reflected by roles of the frontal cortex and limbic system in science-related tasks. Indeed, Potvin et al. (2014) noted that the activation of the anterior insula cortex by novices may have indicated a type of negative emotional response or uncomfortable state related to cognitive conflict or uncertainty. This type of finding may fit well into models such as the dynamic model of conceptual change, which predicts that emotions influence motivation to engage in message consideration, processing, and conceptual change (Nadelson et al., 2018). Educational interventions should assess students' feelings of uncertainty and experiences of cognitive conflict and design experiences to promote deeper conceptual change.

While fMRI studies are promising, combination with multimodal physiological approaches such as eye-tracking, electrodermal activity, heart rate, facial electromyography, electroencephalogram, and hormone levels is also valuable (Villanueva, Husman, Graham, Christensen, & Khan, 2019). By collecting multimodal data, we would be better able to understand the cognitive and affective factors at play during conceptual change. For example, fMRI provides evidence of cognitive processes, but not emotional engagement (Villanueva et al., 2019). Combined with eye-tracking and electrodermal activity, such a study would provide indepth insight into the cognitive, visual, and affective engagement of a learner.

While there is great potential in educational neuroscience research filling gaps in educational literature concerning cognitive and affective changes in learners, it is not without some drawbacks. Interdisciplinary work is necessary, combining the skills and methods of those in neuroscience research with the theory and research questions of those in conceptual change and science education research. In addition, access to and use of neuroimaging equipment can be difficult and is expensive, often leading to studies with small numbers of participants. However, these factors should not deter us from forming collaborative partnerships with skilled researchers in other disciplines and pushing the field forward.

CONFLICT OF INTEREST

The authors declare no conflicts of interest.

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