THEORETICAL ARTICLE

Proposition for improving the classical models of conceptual change based on neuroeducational evidence: conceptual prevalence

Patrice POTVIN[1, *]

[1] Université du Québec à Montréal
[*] E-mail : potvin.patrice@uqam.ca

Abstract

In this article we propose some adjustments to the models of conceptual change that belong to the "classical" tradition for the purpose of improving the efficiency of science teaching that aims at producing such "conceptual changes". These adjustments are suggested on the basis of recent research results in neuroeducation and psychopedagogy. We first present a synthetic description of the classical tradition of conceptual change, its founding principles, and the literature that supports it, as well as pointing out some of its shortcomings. Next, we present the relevant results that call the model into question, and we propose some adjustments in the form of a three-step procedure that we believe can better produce appropriate "conceptual prevalence." Finally, we present plausible implications of the discussed neuroeducative findings for learning in general.

1. Introduction

1.1 Teaching for conceptual change in real-life contexts

There is absolutely no doubt that the most cited and most influential model of conceptual change was proposed by Posner, Strike, Hewson, and Gertzog (1982), which we will refer to as "PSHG" throughout the following article. This model, which was mainly inspired by the Piagetian concept of accommodation (Piaget, 1968) and by the Khunian concept of "scientific revolution" (Kuhn, 1962), addresses the difficult problem of making learners modify the "misconceptions" they hold about how the physical world works.

Most of the time these "misconceptions" are defined by their inconsistency with scientific knowledge. They have also been widely known to be persistent and hard to change (diSessa, 2006). And even though the term "misconceptions" has been widely accepted and frequently used in research and teacher training, it has still been severely criticized by the scientific community of educators for not recognizing the ecological validity (in everyday life) of many students' ideas (Caravita & Hallden, 1994). Indeed, these misconceptions, even though they do not conform to knowledge that is recognized by the scientific community, can still be very useful and sometimes more than sufficient for students to lead productive lives. The use of the term "misconception" has also been criticized because its public utilization puts learners' pride and self-confidence at risk (Stavy, 1991) because of its negative connotations (Abimbola, 1988).

We all agree that students should never be demotivated by educational discourse or reduced to passive "receivers," but still, it can be argued that the term "misconception" makes sense for describing the real-life difficulties of professional science teachers. Indeed, the first job of a science teacher is to help students meet the requirements prescribed by educational programs. Usually these programs are quite loaded, and in the widespread reality of well-filled classes, teaching brutally becomes normative and cannot succeed as much as it can be "optimized." Therefore, elementary and high school teachers, for example, rarely have the opportunity to invest much time in the exploration, individual treatment, or co-modelisation of individual conceptions. The greater part of their school year is often a race against time in an attempt to cover all the numerous objectives and content-knowledge elements (Perrenoud, 1996) by the end of the semester or school year. In this practical and challenging context, unscientific and unprogrammed conceptions are oftentimes merely perceived as noise interference, and very few teachers are able to devote enough time and energy, or are sufficiently pedagogically knowledgeable or ingenious, to correctly diagnose and address students' conceptions. In this context, one has to admit that most of the time students' misconceptions are understood as mere recurrent difficulties that make students diverge from the intended path, leading to a possible derailment of the educative project. In this realistic perspective, students' non-scientific schemas truly are wanderings, and the term "misconception" might not be too harsh. Sadly, it appears that only researchers and a few teachers who are privileged enough to be responsible for very few children have, for the moment, the luxury to call and treat misconceptions differently, or to study them thoroughly. If one realistically accepts the normative function of school and its economic and ordinary human constraints, then *mis*conceptions can be considered as *mis*takes that, in the end, one way or the other, have to be corrected durably.

That being said, denying the importance of taking into account students' prior knowledge would still seem to be a major pedagogical mistake. Therefore, the classical models of conceptual change, like PSHG's model, might be suitable compromises. Indeed, they give clear, simple, and realistically applicable instructions about the optimal way of favouring conceptual change when needed. In other words, the classical models of conceptual change are operational. For researchers, they offer simple criteria that could easily be used to build operational research protocols or that could facilitate the qualification or disqualification of pedagogical interventions.

1.2 "Classical" models of conceptual change

In the 2008 handbook she edited, Stella Vosniadou defines the "classical approach" of conceptual change as

> the leading paradigm that guided research and instructional practices in the classroom for many years. According to it, the student is like a scientist, the process of (science) learning is a rational process of theory replacement, conceptual change is like a gestalt shift that happens over a short period of time, and cognitive conflict is the major instructional strategy for promoting conceptual change (Vosniadou, 2008, p. xvi).

Among the models that belong to the classical tradition, Nussbaum and Novick's (NN) model of conceptual change is a strong example (Nussbaum & Novick, 1982). This model suggests that teachers should (1) expose alternative frameworks, (2) create a conceptual conflict, and (3) encourage accommodation. The same kind of sequence was proposed in PSHG's model. In short, it proposed to (1) provoke learners' dissatisfaction toward their own misconceptions by any means necessary (as in Nussbaum's "exposing event" [1982]), and then present the scientific conception to learners in order for it to be (2) intelligible, (3) plausible, and (4) fruitful. According to the model, following these criteria would encourage learners to "replace" (Posner et al., 1982, p. 213) their therefore discredited non-scientific conceptions with the programmed ones or, at least, accommodate them with the presented "discrepant events." The order in which these pedagogical operations has to be conducted is not always perfectly clarified, but most of the time dissatisfaction is presented as "the first crucial step" (Nussbaum & Novick, 1982, p. 187).

PSHG's and NN's models can be considered as prototypical examples of the classical tradition of conceptual change, which has "cognitive conflict" as its central concept (Chan, Burtis, & Bereiter, 1997). It also became somewhat implicit to almost the entire field that conceptual or cognitive conflict has to be the "first step to achieve conceptual change" (Limon, 2001, pp. 359, 369). Scott also talks about the strategies "where conflict must be recognized by the student *in the early stages* of teaching if learning is to occur" (Scott, Asoko, & Driver, 1991, p. 76).

> The classical conceptual change approach involved the teacher making students' alternative frameworks explicit prior to designing a teaching approach consisting of ideas that do not fit the students' existing ideas and thereby promoting dissatisfaction (Duit & Treagust, 2003, p. 673).
>
> Following Dewey (1910), it is generally agreed that accommodation necessitates *first of all* recognition by the learner of a problem and his inability to solve it with his existing conceptions (Nussbaum & Novick, 1982, p. 186).
>
> *Before* an accommodation will occur, it is reasonable to suppose that an individual must have collected a store of unsolved puzzles or anomalies and lost faith in the capacity of his current concepts to solve these problems (Posner et al., 1982, p. 214).

Many other models of conceptual change were subsequently proposed by authors in order to go beyond the classical model tradition. Among (Carey, 1985; Chi, 1992; Thagard, 1992), some were mostly derivatives (Hewson, 1981) of the PSHG model, while others mainly provided analogies (Giordan, 1991). Some were quite difficult to grasp (diSessa, 1993) or to concretely apply (Vosniadou, 1994; Vosniadou & Brewer, 1992), while others were effective only in certain contexts or were limited to specific content knowledge (see Potvin (2011) for more descriptions of conceptual change models). We believe that these “second-generation” models belong to what Ohlsson (2009) might describe as “transformation-of-previous-knowledge” (p. 20) models, that opposed the classical tradition by rejecting the idea that initial conceptions can be abandoned. Furthermore, “not all of these second-generation models were developed to be applied to the context of school learning” (Limon, 2001, p. 358). One cannot say that the models that followed were inefficient or uninteresting, or that they did not contribute significantly to the field; however, we believe that none of them reached enough teachers and researchers to become a leading model and supplant the ones that belong to the classical tradition.

1.3 Dissatisfaction with the classical tradition

Though very popular, the classical models have been criticized for their “naïveté” and because they were viewed as oversimplifying the complex reality of learning, considering the time it usually takes to learn, the numerous setbacks and iterations it seems to require, and the emotional and personal considerations it involves.

Thousands of articles report the effectiveness of the approach with more or less strength, but very few record neutral results, and almost none report negative results (Duit, Treagust, & Widodo, 2008). Nevertheless, the classical models have not completely satisfied the research community.

A first source of dissatisfaction might be linked to the use of the term “conceptual *change*.” Implicit in this expression is the idea that if conceptual *change* succeeds, then initial conceptions cannot be left intact. They have to be, according to the concept of change, either completely abandoned (Villani, 1992), modified (Limon, 2001), replaced (Posner et al., 1982, p. 212), reorganized (Jensen & Finley, 1995, p. 149), eliminated (Nersessian, 1998), rejected (Hewson, 1981, p. 385), transformed, or “restructure[d]” (Limon, 2001, p. 359).

It is therefore not surprising that conceptual change research has concentrated very little energy on analyzing what happens after change occurs. Indeed, if the objective is to get right answers (which are considered reliable clues that initial conceptions were indeed “changed”), then right answers must indicate the success of the process, and therefore its termination. In the demanding real-life context of teaching, they might also indicate that it is time to get interested in the following topic.

A second source of dissatisfaction with the classical models might be linked to the use of the concept of “conception.” When used often, the concept can become familiar enough to become unproblematic. It can lead to some kind of reification. Many aware educators hold personal and prototypical examples of conceptions and think of them as worthy pedagogical target objects. And it might sometimes happen that conceptions become perceived as self-evident, monolithic, or thought-as-real objects. Many teachers and even researchers have thus confused students’ justifications (for producing such and such answer) with authentic conceptions. It is true that until recently conceptual change research has been limited to questionnaires, interviews, and pre-post designs. It is also true that many famous conceptions have been labelled with the words students use to talk about them, but it appears more reasonable to think of students’ answers and justifications (which questionnaires or interviews reveal) as mere indirect by-products of conceptions, inclinations, or intuitions. If so, conceptions would benefit from somewhat of a “desecration” and by being understood as mere shadows, as in Plato’s allegory of the cave (Potvin, 2011, p. 230). To confuse answers with conceptions might lead to the presumption that a change in answers is a change in conceptions or might lead to important errors in targeting (because mere answers cannot be as complex or complete as conceptions, or entire networks of intuitions). Therefore, as we have argued before (Potvin, Masson, Riopel, & Fournier, 2007), students’ justifications might not be in all circumstances adequate objects of pedagogical treatment, nor might they inform us of the process by which they appear, or last. It therefore might not be enough to obtain an incorrect-but-coherent answer in order to declare war on the conception it is supposed to represent. As Stavy and Tirosh suggest, conceptions might actually only be specific instances of the use of intuitive rules (2000, p. 2).

Many conceptions that are revealed by questionnaires or interviews might also be considered as rigid and lasting objects, but they could also have been constructed a minute ago, on the spot, for the sole purpose of satisfying the interviewer, on the simple basis of plausibility.[1] This occurs frequently in science classes where students are obligated to produce answers on tests, even though they really have nothing to say. So if “conceptions” are

[1] We had previously called “instantaneous constructivism” the “on-the-fly” (diSessa, 2002) construction of conceptions (Potvin, 2007).

sometimes instantaneous constructions, they could also be more fragile or ephemeral than expected. Some of our previous work, based on extended interviews, argues that many answers expressed with confidence—and presumably based on conceptions—are in fact quite fragile, and learners often stop insisting on using them as soon as the slightest ineffectiveness is noticed (Potvin & Thouin, 2003). Other research initiatives based on transcriptions show that in fact, when students explain certain phenomena, they rarely mobilize well-structured conceptions (von Aufschnaiter & Rogge, 2010). Therefore, beginning a sequence by cognitive conflict might be completely ineffective because the presumed conception to put in conflict might not be present, or it might be in a diffuse form that is too slippery to smash through.

For these and other reasons, the classical tradition of conceptual change has not been fully satisfactory in explaining what happens when conceptions (or answers) "change," nor to produce enough successful concrete results. In early research, the few pedagogical prescriptions that emerged from studies based on classical models were said to work some of the time, but not always (Eylon & Linn, 1988; Guzetti, 1993; Limon & Carretero, 1997; Tillema & Knol, 1997), and misconceptions were therefore even more considered as "highly robust" and resistant to change (Brown & Hammer, 2008). Old conceptions were also sometimes observed to, even "after short periods of time after the instructional intervention" (Limon, 2001, p. 364), inexplicably come back to life, intact, or unexpectedly mixed with parts of new knowledge (Hammer, 2000). Students were understood as often "unable to achieve meaningful conflict or to become unsatisfied with their prior conceptions" (Chan et al., 1997, p. 2), even in cases where much effort was invested in introducing meaningful discrepancies (Dreyfus, Jungwirth, & Eliovitch, 1990; Jensen & Finley, 1995). Some cases were also reported where students "reinterpreted anomalous data incorporating them into their answers by making an extension of their initial hypotheses" (Limon, 2001, p. 363).

Many research and teaching initiatives also focused on identifying the origins of conceptions (Thouin, 2001), believing that if their roots could be better known, then recurrent errors might be prevented, or more efficiently treated, because they would be addressed in a more fundamental way. But these efforts were not, in our opinion, successful. Misconceptions were phenomenological (diSessa, 2004), social (Perret-Clermont, 1996), experiential, or based on core intuitions (Brown, 1993), automatic mental habits (Fischbein, 1987), intuitive rules (Stavy & Tirosh, 2000), and frameworks (Vosniadou & Brewer, 1992), etc. The multiplicity of their origins, added to the multiplicity of their forms, from one culture to another (Loubaki, Potvin, & Vazquez-Abad, 2012; Stavy et al., 2006), from one learner to another, made the task of diagnosing all the possible conceptions ecologically unviable, and the possibility of intervening adequately on all of them even more unviable.

But if “this strategy has not been successful as expected” (Limon, 2001, p. 359) to produce the desired changes in students, and even with the lack of precision in “what changes in conceptual change” (diSessa & Sherin, 1998), the classical tradition, we argue, has rarely been seriously threatened, reconsidered, or modified. After all, it is so far the best, simplest, and most operational tool teachers have to ascertain corresponding difficulties and, without a better alternative, there is no reason to abandon it. Doing so, a teacher or a researcher might appear like “the carpenter who blames his tools.”

2. New findings about how the brain works

Recently, findings from neuroscientific and neuroeducational research, that might shed light on the conceptual change issue, have been published.

2.1 Neuroimaging research on scientific expertise

Differences between experts and novices have been thoroughly investigated in many contexts. Many definitions of experts exist, but in conceptual change studies, participants who give right answers to questions involving common misconceptions can be considered as learners that have gone through the process of conceptual change successfully. Even though there is no certainty that these experts once believed in or held the studied misconceptions, there is a good chance that they once held them if these misconceptions are frequently observed at early ages.

Therefore, if longitudinal studies about conceptual change are difficult to manage, the transversal study of differences between novices and experts can be considered as a good approximation of conceptual change learning.

Recently, a growing number of studies have shown interest in the differences in cerebral activations between novices and experts during scientific tasks involving common misconceptions. Some of these studies were conducted in Canada, in different scientific fields. Dunbar, Fugelsang, & Stein (2007), for example, and Brault Foisy, Masson, Potvin, & Riopel (2012) studied misconceptions involving falling objects. Masson (Masson, Potvin, & Riopel, 2010a, 2010b; Masson, Potvin, Riopel, & Brault Foisy, submitted) also studied misconceptions in basic electricity, and Nelson, Lizcano, Atkins, & Dunbar (2007) studied misconceptions in chemistry. These authors have been able to show that when experts succeed in scientific tasks, they activate brain mechanisms usually associated with the function of inhibition, as seen when people perform Stroop (MacLeod, 1991) or "Go/no-go" (Rubia, Russel, & Overmeyer, 2001) tasks. In this case, inhibition is understood as a brain function that allows resistance to distractors and interferences (Houdé, 2008).

The cerebral regions involved in these tasks are the prefrontal cortex (ventrolateral and dorsolateral cortices) and sometimes the anterior cingulate, which is usually associated with the detection of conflict (Botvinick, 2007). A conceptual interpretation of these results would support the hypothesis that conflict and inhibition still exist in the minds of experts even though they are not necessarily aware of it (Masson, Potvin, Riopel, Brault Foisy, & Lafortune, 2012).

If experts are considered (as they are by these authors) as learners who have gone through a scientific conceptual change, then the activation of inhibition mechanisms raises the question of what has been inhibited. In every case, the authors' interpretations point to the initial but no longer prevailing misconceptions. Therefore, all of these authors conclude that there is a coexistence of scientific and non-scientific schemas within the experts' minds.

Other recent results (Houdé et al., 2011) obtained with children using a typically Piagetian conservation task also lead to interpretations involving inhibition. Houdé suggests that even at a very early age (5–6 years), development in logical functions might well be explained by the development of inhibition (activation of prefrontal regions). We believe that these results are interesting for science education because much of basic scientific knowledge and many difficulties involve conservation errors, but Houdé goes much further, affirming that "development is all about learning to inhibit"[2] (Théodule, 2005). Houdé also makes a strong case in favour of inhibition-based explanations for object, number, categorization, and reasoning tasks (Houdé, 2000), involving functions obviously important for learning science.

[2] "Se développer, c'est apprendre à inhiber."

2.2 Research on accuracy and reaction times

As argued before, conceptual change research has not always been interested in what happens after accurate answers are produced, but there is a growing body of evidence that suggests that even when accurate answers are given, conflict still exists. These research projects are mainly interested in reaction times, and use equivalently difficult questions that differ by the fact that common misconceptions are presumed to interfere with (questions often labelled "counter-intuitive") or encourage (those labelled "intuitive") the production of scientifically accurate answers.

It is argued that if some correct answers require more time to be produced than others, it is because they require more demanding cognitive procedures. In tasks used by researchers (because differences in time reactions have been associated with differences in the involvement of common misconceptions), lags have been attributed to the suppression of initial conceptions.

Results that support this hypothesis were obtained by Babai and Amsterdamer (2008) in conceptions about solids and liquids, and by Babai, Sekal, and Stavy (2010) about living things. In a very convincing way, results were also obtained by Shtulman and Valcarel (2012) in no less than 10 scientific domains. A kind of lag called "negative priming" has also been recorded for right answers immediately following counter-intuitive questions, suggesting the presence of inhibition (Babai, Eidelman, & Stavy, 2012). Reaction times to a buoyancy task have also been studied by Lafortune, Masson, & Potvin (2012) in a developmental study, and they concluded that inhibition is most likely involved in the explanation of the improvement of answers as children grow older (ages 8–13).

2.3 Other research

Other research initiatives have also contributed to the idea that anterior knowledge does not disappear with learning, but remains active, though not always prevalent. When subjects with Alzheimer's disease (a condition well known to weaken executive functions such as inhibitive functions) are offered the choice between naïve or scientific answers, more often they choose teleological (Lombrozo, Kelemen, & Zaitchick, 2007) or animistic (Zaitchick & Solomon, 2008) ones (both typical of behaviour displayed by young children). This suggests that these explanations, to which the subjects most likely adhered to in their childhood, in fact never ceased to intervene in their decision making, even though they were not prevalent during their entire life until the onset of the disease. A similar effect can be observed when normal subjects are required to produce answers more rapidly. These situations, known to weaken inhibition, reveal the presence of teleological (Kelemen & Rosset, 2009) and non-scientific conceptions, even with professional scientists (Kelemen, Rottman, & Seston, 2012).

Other research projects have attempted with some success to estimate the share of inhibition in the prediction of conceptual gain. It appears that inhibition can explain from 18 (Thibault, 2013) to 29 percent (Kwon & Lawson, 2000) of the conceptual gain in certain tests, including the well-known *Force Concept Inventory* (Hestenes, Wells, & Swackhammer, 1992), in a semester.

2.4 What can be learned of these results?

As these kinds of results accumulate, it becomes clearer and clearer that conceptual change models should benefit from integrating the idea that initial misconceptions are not restructured, replaced, or abandoned by learners, even though students happen to produce accurate answers or even though they eventually become experts.

It would be unfair to claim that this idea had never been suggested before in the field of conceptual change. Indeed, some authors had already argued that conceptions might not be rejected or replaced (Solomon, 1983; 1984). Mortimer (1995), for example, suggested that changing conceptions could merely be changing “profiles” and explains that

> [o]nly a few authors have explicitly recognised the impossibility of effecting this kind of change which results in the replacement of the student's initial ideas. Solomon has pointed out “that means should not be found to extinguish them (the everyday notions)” (Solomon 1983, p. 49-50). More recently Chi (1991) showed the possibility of the coexistence of two meanings for the same concept, which are accessed in the appropriate context. Linder (1993) argues that this coexistence is possible even within scientific concepts and illustrates this thesis with examples from mechanics, optics and electricity, where the classical and modern views of the same phenomena are not consonant (p. 268).

In a commentary article, Spada (1994) had also suggested that “multiple representations” could coexist and that old beliefs “do not have to be replaced. In particular, they think that misconceptions are very predictive and useful in daily life, so they do not have to be abandoned” (Limon, 2001, p. 363).

Some authors have also argued that, at least for the first steps of conceptual change, there might be a competition between coexisting theories: “[d]uring a large part of the learning process, students are elaborating new academic models without leaving behind their spontaneous models, and it ought to be considered, in many cases, a normal and rational behaviour” (Villani, 1992, p. 231). Even Strike and Posner have suggested that “competition between conceptions results in a process of accommodation characterized by temporary advances, frequent retreats, and periods of indecision” (1985, p. 221). This indecision suggests coexistence, even if the final objective still remains accommodation, and therefore restructuration of knowledge. Duit and Treagust (2003) have also suggested that “when a competing conception does not generate dissatisfaction, the new conception might be assimilated alongside the old, which Hewson (1981) calls ‘conceptual capture’ ” (p. 676).

Most of such arguments, that appeared sporadically in the science education literature, were however rather marginal, usually epistemology-based and were mostly theoretical suggestions. We believe that the neuroscientific results described in the three previous sections bring important additional experimental arguments for the coexistence claim and that efforts should now be made to fully extrapolate the consequences that come with the idea that conceptions continue to exist within learners’ cognitive decision-making process and interfere (more or less), even if they sometimes do not prevail. In this context, forgetting seems to be unlikely, and expertise and “conceptual change” appear to be more about making appropriate intuitions prevail than having the non-scientific ones altered. The inexplicable and disappointing “resurrection” of many initial conceptions that were presumed to be “defeated” by training becomes, in this sense, unproblematic: training merely made some other function temporarily supplant them. Hypotheses about reasons why they started to prevail again are easy to imagine: they were reinforced somehow (either socially or through interaction with the environment) and their status was therefore increased, supplanting again what had supplanted them before. This idea of a dynamic competition between “overlapping waves” has been well illustrated by Amélie Lubin (Lubin, Lanoë, Pineau, & Rossi, 2012) and by Sandrine Rossi (Rossi, Lubin, Lanoë, & Pineau, 2012).

The idea of a coexistence between conceptions also suggests that we can think of performance only in terms of prevalence and teaching for scientific conceptual change in terms of strategies that aim at durably increasing the status of the particular inclinations that lead to scientifically correct performances. In this sense, no reduction of adhesion to initial conceptions appears to be likely, appropriate, or useful. “Overtaking” therefore would seem to be the appropriate pedagogical objective to pursue, and only by *adding* information or experiences that have (1) the potential to “block” the increase of a misconception’s status and to (2) sufficiently increase the status of a prescribed conception, can desired prevalence hopefully be obtained.

In this exclusively “additive” “model of conceptual change”, it appears appropriate to (1) obtain the initial availability of programmed conceptions, (2) develop and support watchfulness for contexts where intuitive prevalence produces unwanted performances, and (3) favour durable prevalence of programmed conceptions by meaningfulness and automaticity.

In this context, generating a cognitive conflict at the beginning of a teaching sequence in order to discredit them seems to be as futile as tilting at windmills, because at this stage learners have nothing to attach discrepant events or arguments to (incommensurability). This might explain why cognitive conflict (viewed as a preliminary step) has not been fully satisfactory. Cognitive conflict might benefit more from occurring at a moment when the availability of a fully credible competitor has already been achieved. As Koslowski and Maqueda (1993, p. 113) suggest, “for confirmation and disconfirmation to be significant, a hypothesis must be tested not merely against alternative hypotheses, but against alternatives that are plausible.”

This suggestion is also reinforced by an fMRI study conducted by Fugelsang and Dunbar (2005), whose results support the idea that when they are exposed to apparently non-plausible possibilities, subjects’ brains treat these possibilities as mere errors, and actively turn away their attention.

Kuhn (1962), one of the main inspirations of PSHG’s model, had also argued that (italics added)

> a scientific theory is declared invalid only if an alternate candidate is available to take its place [...]. The decision to reject one paradigm is always *simultaneously* the decision to accept another, and the judgment leading to that decision involves the comparison of both paradigms with nature and with each other" (p. 77);

and

> [t]o reject one paradigm without *simultaneously* substituting another is to reject science itself. That act reflects not on the paradigm but

> on the man. Inevitably he will be seen by his colleagues as "the carpenter who blames his tools" (p. 79).

3. Operational proposition for improving the classical tradition of conceptual change

We present here a detailed and complete version of our proposition so that the reader can better understand the numerous operational (teaching) implications of neuroeducative research results. Such a proposition would, *before anything else,* favour the

1. *availability of the programmed (desired) conception*. This is the first fundamental difference with the classical models, which suggest *beginning* a teaching sequence with a cognitive or conceptual conflict. From a "prevalence" perspective, conflict has meaning only in the context of competition; learners should therefore be given the chance to benefit from the availability of a "new branch" to grab onto before being invited or incited to let go of the "old one." Respecting this condition might therefore avoid, in our opinion, students treating the eventually presented scientific conceptions as errors (Fugelsang & Dunbar, 2005). The Adaptative Behavior and Cognition research group also demonstrated the importance and role of the "recognition heuristic" in the decision-making process. This heuristic immediately makes familiar information or functions more valuable and credible to the eyes of a person than another information or function, that is less familiar[3] (Gigerenzer & Todd, 1999). In the race to prevalence, the first thing that is evoked might therefore benefit from some kind of head start. To use Ohlsson's words, "This implies, in turn, that the theory will be applied more often, which gives it yet more opportunities to demonstrate its utility and hence again further advantages over its competitor" (2009, p. 29). On the contrary, attacking misconceptions (thereby evoking them) at the beginning of the sequence might accidentally boost their familiarity, and therefore their credibility or status. Making this exercise "public" also puts learners who did not initially adhere to misconceptions at risk of being "contaminated." This risk was already well demonstrated by Hynd, McWorther, Phares and William (1994) when she studied the effects of free discussions between

[3] For example, this heuristic is often used in publicity, where presenting a mere logo is enough to increase perceived credibility and sales, or to better understand situations where the popularity of a person is sufficient to trigger additional credibility and interest.

students. We believe that beginning the teaching sequence with a conceptual conflict could still be useful, but since not every student will adhere to the targeted misconceptions, then it will be at least partially useless. To obtain availability, PSHG's condition of "intelligibility," taken integrally, in our opinion seems to be extremely relevant. It is also possible that plausibility has to be discussed with learners at this stage, to encourage them to consider—either consciously or not—the new conception as a worthy opponent. We also suggest that the proposition of beginning teaching sequences with availability is quite in line with research results that explain why students with the best "prior knowledge" will benefit more from the conceptual change classical models (Chinn & Brewer, 1993; Limon, 2001; Limon & Carretero, 1997). In fact it is plausible that the reason why the classical models work better with them is that the condition of availability (or initial assimilation) of scientific conceptions (or either parts of them or crucial information about them) is initially already fulfilled for these learners, therefore making a meaningful cognitive conflict possible right at the beginning of the teaching sequence. In compliance with this interpretation, we have already shown that students with a higher feeling of certainty benefit more from conceptual change interventions (Potvin, Riopel, Masson, & Fournier, 2010) than others who express uncertainties about the answers they propose. Once availability is obtained and confirmed (and only then), we suggest that there must be

2. *installation of inhibitive "stop signs."* Since the adhesion of a learner to a misconception cannot be weakened, it must not in any way be allowed to strengthen during the teaching sequence. Therefore, it appears that learners must be made aware of the insufficiencies of their misconceptions and warned that in certain identified contexts, they have limits. These limits must be shown through any crucial demonstration (logical, rhetorical, experimental, based on analogies, examples, cases, etc.) that can be made. It is basically the same condition of "dissatisfaction" from PSHG's model except that, instead of being done with the goal of discrediting misconceptions by clear exposition or explicitation, it is done for the sole purpose of obtaining the correct recognition of particular contexts where they lead to errors. Instead of falling into dialectic psychoanalyses of misconceptions or argumented refutations, a simple "in such and such circumstances, it appears intuitively tempting to think or to answer in such and such way, but we shouldn't, because this often leads us to make such and such errors," might be enough, assumed that arguments or credible demonstrations

are also provided, when possible. In this perspective, leading extended and heavy epistemological assaults on presumably present misconceptions would be pointless because “lowering the status of [...] alternative conceptions to allow conceptual exchange [...] or reconciliation” (Hewson, 1981, p. 395) is unlikely to happen. Ohlsson also argues that the “anomaly-accumulation theory” (2009, p. 23) has not been proven effective enough and rather supports theories, like “resubsumption”, that prevents the difficulties of cognitive conflict by avoiding conflicts altogether. We will not go that far, but we nevertheless believe that efforts to produce conflicts and refutations might sometimes unfortunately lead to all kinds of confusions. In our view, simple demonstrations of the ineffectiveness (in certain contexts) of certain predictions might often be sufficient. From our perspective, when teachers are able to notice the development of strong enough inhibitive reflexes about major misconceptions, they can move on to the next step (less frequent incorrect intuitions can be dealt with later, during more personalized interventions). The limits of misconceptions can be shown, we believe, through cognitive conflict, by introducing discrepant events or potentially surprising outcomes. In this context, asking learners to explicitly predict the outcome of a demonstration, for example, is a very interesting strategy that helps teachers to better diagnose undesired intuitions. At the same time, it betrays students’ adhesions while making subsequent denial hard to defend. In our opinion, this kind of conflict is pedagogically interesting because it makes learners aware of the importance of installing in themselves a systematic watchfulness and the reflex of holding back their first intuitions when needed, but nothing more. Houdé has already shown, with PET scan research, that simple warnings about the possible existence of traps are often sufficient to completely change the brain’s reactions to stimuli, and to transfer rear activation into frontal activation in logics tasks (Houdé et al., 2000). Similarly, students could be invited, within simple metacognitive discussions, to become vigilant when it is appropriate. We have also shown in previous research that, assuming students are able to experimentally test their hypotheses, initial exchanges of personal conceptions do not lead to contamination (Potvin, 2012). We therefore suggest that cognitive conflicts should preferably be induced by experimental means, letting nature reinforce (or not) the available conceptions or intuitions. These means should be numerous, rich, and astute in order to prevent any important misleading intuitions from eluding teachers’ efforts. In our opinion, designing such means is one of the most stimulating parts of the professional work of a teacher. Once availability of the desired conception is obtained and adequate "stop signs" or "warning signs" are installed in front of certain intuitions or misconceptions, we propose to work for

3. *durable prevalence of the programmed conception*. It appears to be rather easy to obtain the short-lived prevalence of an intuition. In our previous work, we were able to show that minimal conflict can easily lead to at least short-term changes in behaviour toward a problem (Potvin, 2010) or question (Richer, 2010). But the durability of a conceptual change is something else. In these research projects, we have observed many "revivals" of previously abandoned conceptions, simply caused by short interruptions in exploration sessions (Potvin, 2010). It seems that recent experiences can have strong but brief influence on the status of a conception, and that they must not, if taken alone, be considered as having the potential for long-term effects. We believe that conceptual change often fails because this problem is underestimated and not addressed properly. If we consider conceptual prevalence instead of conceptual transformation, then the appropriate attitude toward initial misconceptions, from the moment they cease to manifest themselves, would be to consider that they have not been defeated and are, most likely, just temporarily supplanted or masked (Shtulman & Valcarel, 2012), waiting for the slightest opportunity to be reinforced and possibly come back again later as prevalent ones. We believe that durable prevalence requires automaticity, and that PSHG's fruitfulness criteria could be of use here. But we do not believe that the purpose of this criteria would be to "resolve its predecessor's anomalies" (Posner et al., 1982, p. 222). We agree with them, however, that it can "lead to new insights and discoveries, [making] the new conception [...] appear fruitful and the accommodation of it [...] seem persuasive" (*ibid.*). But above all, we agree that it must be conducted for the sake of automaticity, which is the key to durable prevalence and true expertise. In this case, every means is welcome. Teacher training initiatives have striven to convince teachers to use numerous and appropriate examples (common and less common examples, as well as counter-examples [Potvin, 2011, pp. 50-54]), and psychology research is filled with convincing behavioural efforts that studied the conditions under which learning becomes durable. Much of this research as well as down-to-earth teaching experiences also show the importance of repetition. The human brain appears to obey some sort of "law of least mental effort" (Botvinick, 2007). Since research shows that with repetition, it takes less energy to succeed in carrying out a task (Chein & Schneider, 2005), it seems reasonable to assume that eventually automated knowledge (conceptions) will inevitably be intuitively

preferred. It also seems important to reinforce not only the desired conceptions but also the “inhibitive stop signs” that were previously installed (step 2). We do not mean that teachers should explicitly address the topic of the interfering misconceptions with extended discussion or argumentation, but simply that they should repeatedly exercise reflexes of inhibiting certain “temptations” (regardless of their nature) that lead to the unscientific treatment of problems or questions in the contexts in which they occur. Therefore, the numerous problems learners should be subjected to should offer a rich variety of contexts, often containing classic lures that correspond to classic errors. These reinforcement programs should extend over time to ensure durability. We believe that it is only when automaticity is achieved that enough cognitive resources are freed to authorize a more thorough comprehension. Automaticity can therefore be understood as an important prerequisite for expertise.

The few differences between this prevalence model and the classical one are mostly about the order in which the operations are conducted and the precise nature of the goals that they pursue. In this vocational conversion, “intelligibility” and “plausibility” would lead to achieve availability. Cognitive conflicts would be conducted not to obtain dissatisfaction, which has been recently argued as almost impossible (Ohlsson, 2009), but to install durable watchfulness. The fruitfulness criteria would be met mostly to favour automaticity. Not only because it favours the credibility of the desired conception with every new context of application, but also because every new attempt to favour fruitfulness is also another repetition.

Our perspective fully acknowledges the normative aspect of teaching, in which certain conceptions are programmed and that these conceptions have to prevail at the end of the teaching sequence (and this has to be achieved in a minimal amount of time). In this way, “conceptual change” sequences are closer to behaviourism-inspired sequences[4] but in our opinion, the proposition still has strong constructivist components because it systematically considers the initial implicit and explicit knowledge. Also, cognitive conflict operations are still intended, even if what they aim at achieving differs slightly.

To better illustrate our perspective, we used an analogy involving a forest, in which conceptions are compared to trails that are progressively cleared (or “carved”). The more these trails are frequented, the more practical they

[4] In the model presented in these pages, conceptions are quite closely associated more with the errors they produce than with hypothetic reified and abstract schemas.

become, and therefore the more they are preferred and used. Since it is impossible (or at least unlikely) to un-clear a trail, the only possible solution to persuade villagers to stop using the trail would be to put a very noticeable stop sign at the start of it and to clear a new and appealing trail to encourage frequent use and consequently familiarization. This use would make the trail wider, which in turn would favour further use and widening. In this analogy, there is no way to prevent the villagers from taking the initial trail. The one we want them to use would have to be preferred.[5]

4. Discussion about the model

4.1 Additional educative consequences of committing to a prevalence model

Even though our "prevalence" proposition suggests that initial conceptions are not altered or discredited, it is not unreasonable to believe that they become, if unused for a long period of time, considerably weakened to the point of being irreparably unprevailing, or even practically eradicated, like a childhood memory that slowly faints and is eventually lost forever. But if the social and physical parameters in which they initially appeared have not changed, it appears difficult to believe that they would never be reinforced or reconstructed on the same basis. We therefore believe that the fight against misconceptions, at least on the scale of science lessons in a school context, would benefit from being considered as unwinnable for good, unless the social environment in which learners live their outside-of-school lives grows richer with scientific conceptions, and therefore durably reinforces scientific prevalence. In this light, it appears even more important to tenaciously favour conceptual change for every individual, in order for society to eventually provide a conceptually interesting ecology in which individuals in return mutually reinforce more scientifically accurate conceptions of their peers.

The prevalence model also highlights the importance of good early instruction. Since conceptual prevalence is so difficult to shift, it suggests that the best situation would be the one where shifting is not necessary. Early acquisition of certain knowledge suggests early prevalence of this knowledge, because the longer an element of knowledge has been available, the more likely it has been reinforced. In the absence of other tools, the owner of a hammer sees everything as a nail, hits it, and consequently increases his or her familiarity with the hammer and its status as a useful tool.

[5] For a better explanation of the model, see Potvin (2011, chap. 10).

Finally, the model also sheds new light on the role of negative reinforcement in learning. For a long time, negative reinforcement was seen as a good way to obtain the extinction of certain behaviours, before it was highly discredited for its negative effect on self-confidence and, in turn, on learning. The prevalence model suggests that it could still be of use, but only if it clearly aims at instilling watchfulness or "warning signs" for errors with the active and metacognitive participation of the learner, and not with the aim of discrediting their conceptions with the hope of extinction. In the long run, we believe that this way of doing things unfortunately causes students' intellectual courage to learn through errors to go extinct instead.

4.2 Misconceptions in a prevalence model

In a teaching context such as the one described above, a "scientific misconception" would be any intuitive belief, inclination, or adhesion (implicit or explicit, large or small) that prevails as the basis of non-scientific treatments of problems, situations, or questions. Within this operational definition, entire mental models, as well as p-prims, intuitive rules, core intuitions, heuristics, or slogans can all be considered as misconceptions, even though the promoters and discussants of these objects would probably not agree. We believe that from a teacher's standpoint (and maybe from a neuroscientific standpoint), they might all be considered as the same: inclinations that must no longer prevail in the light of demanding pedagogical projects such as they exist in school systems today. The perceived need for the existence of such a multiplicity of "conceptual objects" in science education literature might simply be the reaction of the scientific community to the perceived dangers associated with the widespread reification of the idea of conception. It might indeed have been seen as too crude and restrictive, and unable to explain the diversity as well as the invariants that exist within students' reactions to questions. It also could not explain why sometimes misconceptions come back to life after training.

Given more or less time and effort, all "conceptions" should be considered as having the potential to be supplanted by other conceptions that conform more to scientific knowledge, ensuring that educative efforts never lose faith in the ability of students to learn. Conceptual prevalence, in this light, could be defined as the teaching operation that consists of making a scientific conception available and durably prevailing. Misconceptions would then not be "difficult to change," but rather difficult to supplant or overtake.

One has to admit that the prevalence approach might appear to be reductive in its own way. It doesn't allow historic or epistemological perspectives to take their place in the school curriculum because it suggests that supplanting errors is sufficient to educate. We acknowledge this risk. But if conceptual change is the goal, the detours that historic and epistemological approaches require might not always be optimal. A prevalence model is rather a response to the concrete conceptual difficulties of teachers seeking to optimize their practice. In other words, for other goals, other methods might be preferable.

4.3 Further research

We believe that the classical conceptual change tradition has recorded partial success in the past because it partially fulfilled the conditions of a prevalence model. But in order to test the true benefits of the prevalence model over the classical ones, further research has to be conducted and the effectiveness of the prevalence model experimentally tested and compared. Therefore, we encourage all comparative research initiatives that head in this direction.

References

Abimbola, I. (1988). The problem of terminology in the study of student conceptions in science. *Science education, 72*(2), 175-184.

Babai, R., & Amsterdamer, A. (2008). The persistance of solid and liquid naive conceptions: a reaction time study. *Journal of Science Education and Technology, 17*, 553-559.

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.

Babai, R., Sekal, R., & Stavy, R. (2010). Persistance of the intuitive conception of living things in adolescence. *Journal of Science Education and Technology, 19*, 20-26.

Botvinick, M. (2007). Conflict monitoring and decision making: reconciling two perspectives on anterior cingulate function. *Cognitive, Affective, & Behavior Neuroscience, 7*(4), 356-366.

Brault Foisy, L.-M., Masson, S., Potvin, P., & Riopel, M. (2012). *Using fMRI to compare brain activity of novices and experts in science when performing a task in physical mechanics involving common misconceptions*. Paper presented at the Neuroscience and education: 2012 meeting of the EARLI SIG 22, University of London, United Kingdom.

Brown, D. (1993). Refocusing core intuitions: A concretizing role for analogy in conceptual change. *Journal of Research in Science Teaching, 30*, 1273-1290.

Brown, D., & Hammer, D. (2008). Conceptual change in physics. In S. Vosniadou (Ed.), *International handbook of research on conceptual change* (pp. 127-154). New York: Routledge.

Caravita, S., & Hallden, O. (1994). Re-framing the problem of conceptual change. *Learning and instruction, 4*(1), 89-111.

Carey, S. (1985). *Conceptual change in childhood*. Cambridge, MA: MIT Press.

Chan, C., Burtis, J., & Bereiter, C. (1997). Knowledge building as a mediator of conflict in conceptual change. *Cognition and Instruction, 15*(1), 1-40.

Chein, J., & Schneider, W. (2005). Neuroimaging studies of practice-related change: fMRI and meta-analytic evidence of a domain-general control network for learning. *Cognitive Brain Research, 25*, 607-623.

Chi, M. (1992). Conceptual change in and across ontological categories: examples for learning and discovery in science. In R. N. Giere (Ed.), *Cognitive models of science* (pp. 129-160). Minneapolis: University of Minneapolis Press.

Chinn, C. A., & Brewer, W. F. (1993). The role of anomalous data in knowledge acquisition: a theoretical framework and implications for science instruction. *Review of Educational Research, 63*(1), 1-49.

diSessa, A. A. (2006). A history of conceptual change research. In K. Sawyer (Ed.), *Cambridge handbook of the learning sciences* (pp. 167-281). Cambridge, UK: Cambridge University Press.

diSessa, A. A. (2004). Coherence versus fragmentation in the development of the concept of force. *Cognitive Science, 28*, 843-900.

diSessa, A. A. (1993). Toward an epistemology of physics. *Cognition and Instruction, 10*(2), 105-225.

diSessa, A. A., & Sherin, B. (1998). What changes in conceptual change? *International Journal of Science Education, 20*(10), 1155-1191.

Dreyfus, A., Jungwirth, E., & Eliovitch, R. (1990). Applying the "cognitive conflict" strategy for conceptual change - Some applications, difficulties and problems. *Science Education, 74*(5), 555-569.

Duit, R., Treagust, D. F., & Widodo, A. (2008). Teaching science for conceptual change: theory and practice. In S. Vosniadou (Ed.), *International handbook of conceptual change* (pp. 629-646). New-York: Routledge.

Duit, R., & Treagust, D. F. (2003). Conceptual change: a powerful framework for improving science teaching and learning, *International Journal of Science Education, 25*(6), 671-688.

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

Eylon, B., & Linn, M. C. (1988). Learning and instruction: an examination of four research perspectives in science education. *Review of Educational Research, 58*(3), 251-301.

Fischbein, E. (1987). *Intuition in science and mathematics*. Dordrecht: D. Reidel Publishing.

Fugelsang, J., & Dunbar, K. (2005). Brain-based mechanism underlying complex causal thinking. *Neuropsychologia, 43*(8), 1204-1213.

Gigerenzer, G., & Todd, P. M. (1999). *Simple heuristics that make us smart*. New York: Oxford University Press.

Giordan, A. (1991). The importance of modelling in the teaching and popularization of science. *Impact of Science on Society, 41*(164), 321-338.

Guzetti, B. (1993). Promoting conceptual change in science: A comparative meta-analysis of instructional interventions from reading education and science education. *Reading Research Quarterly, 28*(2), 117-154.

Hammer, D. (2000). Student resources for learning introductory physics. *American Journal of Physics 68*(S1).

Hestenes, D., Wells, M., & Swackhammer, G. (1992). Force concept inventory. *The Physics Teacher, 30*, 141-158.

Hewson, P. W. (1981). A conceptual change approach to learning science. *European Journal of Science Education, 3*(4), 383-396.

Houdé, O. (2008). *Les 100 mots de la psychologie*. Paris: Presses Universitaires de France.

Houdé, O. (2000). Inhibition and cognitive development: object, number, categorization and reasoning. *Cognitive Development, 15*, 63-73.

Houdé, O., Pineau, A., Leroux, G., Poirel, N., Perchey, G., Lanoë, C., et al. (2011). Functional magnetic resonance imaging study of Piaget's conservation-of-number task in preschool and school-age children: A neo-piagetian approach. *Journal of Experimental Child Psychology, 110*, 332-324.

Houdé, O., Zago, L., Mellet, E., Moutier, S., Pineau, A., Mazoyer, B., et al. (2000). Shifting from the perceptual brain to the logical brain : the neural impact of cognitive inhibition training. *Journal of Cognitive Neuroscience, 12*(5), 721-728.

Hynd, C., McWorther, Y., Phares, V., & William, S. (1994). The role of instructional variables in conceptual change in high school physics topics. *Journal of Research in Science Teaching, 31*(9), 933-946.

Jensen, M., & Finley, F. (1995). Teaching evolution using historical arguments in a conceptual change strategy. *Science Education, 79*(2), 147-166.

Kelemen, D., & Rosset, E. (2009). The human function compunction: teleological explanation in adults. *Cognition, 111*(1), 138-143.

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*, No Pagination Specified. doi: 10.1037/a0030399

Koslowski, B., & Maqueda, M. (1993). What is confirmation bias and when do people actually have it? *Merrill-Palmer Quarterly, 39*(1), 104-130.

Kuhn, T. S. (1962). *La structure des révolutions scientifiques*. Paris: Champs-Flammarion.

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*(1), 44-62.

Lafortune, S., Masson, S., & Potvin, P. (2012). *Does inhibition have a key role to play in overcoming intuitive interferences in science?* Paper presented at the Neuroscience and education: 2012 meeting of the EARLI SIG 22, University of London, United Kingdom.

Limon, M. (2001). On the cognitive conflict as an instructional strategy for conceptual change: a critical appraisal. *Learning and Instruction, 11*, 357-380.

Limon, M., & Carretero, M. (1997). Conceptual change and anomalous data: A case study in the domain of natural sciences. *European Journal of Psychology of Education, 12*(2), 213-230.

Lombrozo, T., Kelemen, D., & Zaitchick, D. (2007). Inferring design: Evidence of a preference for teleological explanations in patients with Alzheimer's disease. *Psychological Science, 18*(11), 999-1006.

Loubaki, G.-N., Potvin, P., & Vazquez-Abad, J. (2012). Regard didactique sur l'explication des différences de performance des élèves marocains et québécois aux évaluations internationales. *The Journal of Quality in Education, 3*, 137-158.

Lubin, A., Lanoë, C., Pineau, A., & Rossi, S. (2012). Apprendre à inhiber : une pédagogie innovante au service des apprentissages scolaires fondamentaux (mathématiques et orthographe) chez des élèves de 6 à 11 ans. *Neuroeducation, 1*(1), 55-84.

MacLeod, C. (1991). Half a century of research on the Stroop effect: An integrative review. *Psychological Bulletin, 109*(2), 163-203.

Masson, S., Potvin, P., & Riopel, M. (2010a). *Brain-based mechanisms underlying conceptual change in electricity* Paper presented at the Meeting of the special interest group SIG 22 "Neuroscience and education" of the European Association for Research on learning and Instruction (EARLI), Swiss Federal Institute of Technology, Switzerland, Zurich.

Masson, S., Potvin, P., & Riopel, M. (2010b). Brain-based mechanisms underlying conceptual change in electricity. *Frontiers in Neuroscience, Conference Abstract: EARLI SIG22 - Neuroscience and Education*. doi: 10.3389/conf.fnins.2010.11.00064

Masson, S., Potvin, P., Riopel, M., & Brault Foisy, L.-M. (submitted). Do experts in electricity still have in their brain a misconception that must be inhibited?

Masson, S., Potvin, P., Riopel, M., Brault Foisy, L.-M., & Lafortune, S. (2012). Using fMRI to study conceptual change: How and why? *International Journal of Environmental and Science Education, 7*(1), 19-35.

Mortimer, E. F. (1995). Conceptual change or conceptual profile change? *Science & Education, 3*, 267-285.

Nelson, J. K., Lizcano, R. A., Atkins, L., & Dunbar, K. (2007). *Conceptual judgments of experts vs. novice chemistry students: an fMRI study*. Paper presented at the 48th annual meeting of the psychometric society, Longbeach, California.

Nersessian, N. J. (1998). Model-based reasoning in conceptual change. In L. Magnini, N. J. Nersessian & P. Thagard (Eds.), *Model-based reasoning in scientific discovery*. New York: Kluwer Academic.

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

Perrenoud, P. (1996). *Enseigner : agir dans l'urgence, décider dans l'incertitude*. Paris: ESF Éditeur.

Perret-Clermont, A.-N. (1996). *La construction de l'intelligence dans l'interaction sociale*. Berne: Peter Lang.

Piaget, J. (1968). Le point de vue de Piaget. *International Journal of Psychology, 3*(4), 281-299.

Posner, G., Strike, K., Hewson, P., & Gertzog, W. (1982). Accommodation of a scientific conception: Toward a theory of conceptual change. *Science Education, 66*(2), 211-227.

Ohlsson, S. (2009). Resubsumption: A possible mechanism for conceptual change and belief revision. *Educational Psychologist, 44*(1), 20-40

Potvin, P. (2011). *Manuel d'enseignement des sciences et de la technologie : pour intéresser les élèves du secondaire*. Québec: Multimondes.

Potvin, P. (2010). *Regard épistémique sur une évolution conceptuelle en physique : une recherche qualitative qui s'intéresse à l'intuition en sciences*. Éditions Universitaires Européennes (EUE).

Potvin, P. (2007). Enseigner les sciences en considérant le rôle de l'intuition dans l'apprentissage des sciences. In P. Potvin, M. Riopel & S. Masson (Eds.), *Regards multiples sur l'enseignement des sciences* (pp. 356-377). Québec: Multimondes.

Potvin, P., Masson, S., Riopel, M., & Fournier, F. (2007). *Intentional conceptual change at issue: Do secondary school science students know when they don't know?* Paper presented at the National Association for Research in Science Teaching 2007 conference proceedings. New Orleans.

Potvin, P., Riopel, M., Masson, S., & Fournier, F. (2010). Problem-centered learning vs. teaching-centered learning in science at the secondary level: An analysis of the dynamics of doubt. *Journal of Applied Research on Learning, 3, Article 5*, 1-24.

Potvin, P., & Thouin, M. (2003). Étude qualitative d'évolutions conceptuelles en contexte d'explorations libres en physique-mécanique au secondaire. *Revue des Sciences de l'Éducation, 29*(3), 525-544.

Richer, J. (2010). *Instantanéité de la construction de la réponse suivant une exposition à un phénomène contre-intuitif de changement de phase en science*. Unpublished master's thesis, Université du Québec à Montréal, Canada.

Rossi, S., Lubin, A., Lanoë, C., & Pineau, A. (2012). Une pédagogie du contrôle cognitif pour l'amélioration de l'attention à la consigne chez l'enfant de 4-5 ans. *Neuroeducation, 1*(1), 29-54.

Rubia, K., Russel, T., & Overmeyer, S. (2001). Mapping motor inhibition: Conjunctive brain activations across different versions of Go/No-Go and Stop tasks. *Neuroimage, 13*(2), 250-260.

Scott, P. H., Asoko, H. M., & Driver, R. (1991). Teaching for conceptual change: a review of strategies. In A. Thibergien, L. Jossem & J. Bajoras (Eds.), *Connecting research in physics education with teacher education* (pp. 71-78). The International Commission on Physics Education.

Solomon, J. (1983). Messy, contradictory, and obstinately persistent: a study of children's out-of-school ideas about energy. *School Science Review*, *65*(231), 225-229.

Solomon, J. (1984). Prompts, cues and discrimination: the utilization of two separate knowledge systems. *European Journal of Science Education*, *6*(1), 63-82.

Spada, H. (1994) Conceptual change or multiple representations? *Learning and Instruction, 4*, 113-116.

Shtulman, A., & Valcarel, J. (2012). Scientific knowledge suppresses but does not supplant earlier intuitions. *Cognition, 124*, 209-215.

Stavy, R. (1991). Using analogy to overcome misconceptions about conservation of matter. *Journal of Research in Science Teaching, 28*(4), 305-313.

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*(3), 417-436.

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

Strike, K. A., & Posner, G. J. (1985). A conceptual change view of learning and understanding. In L. H. T. West & A. L. Pines (Eds.), *Cognitive structures and conceptual change* (pp. 211-231). Orlando: Academic Press.

Thagard, P. (1992). *Conceptual Revolution*. Princeton, NJ: Princeton University Press.

Théodule, M.-L. (2005). Olivier Houdé: "Se développer, c'est apprendre à inhiber". *La Recherche, 388,* 74-77.

Thibault, F. (2013). *Étude du rôle de l'inhibition dans l'évolution du concept de force chez des étudiants universitaires en physique*. Unpublished master's thesis, Université du Québec à Montréal, Canada.

Thouin, M. (2001). *Notions de culture scientifique et technologique. Concepts de base, percées historiques et conceptions fréquentes*. Québec: Multimondes.

Tillema, H. H., & Knol, W. E. (1997). Promoting student teacher through conceptual change or conceptual instruction. *Teaching and Teacher Education, 13*(6), 579-595.

Villani, A. (1992). Conceptual change in science and science education. *Science Education, 76*(2), 223-237.

von Aufschnaiter, C., & Rogge, C. (2010). Misconceptions or missing conceptions? *Eurasia Journal of Mathematics, Science & Technology Education, 6*(1), 3-18.

Vosniadou, S. (2008) International handbook of research on conceptual change. New York, NY: Routledge.

Vosniadou, S. (1994). Capturing and modeling the process of conceptual change. *Learning and Instruction, 4*(1), 45-69.

Vosniadou, S., & Brewer, W. F. (1992). Mental models of the earth: a study of conceptual change in childhood. *Cognitive Psychology, 24*(4), 535-585.

Zaitchick, D., & Solomon, G. E. (2008). Animist thinking in the elderly and in patients with Alzheimer's disease. *Cognitive Neuropsychology, 25*(1), 27-37.