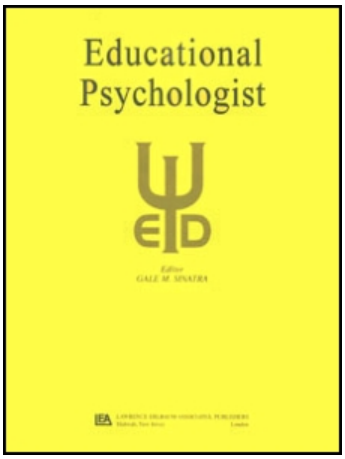

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Contrasting Ohlsson's Resubsumption Theory With Chi's Categorical Shift Theory

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Ohlsson's proposal of resubsumption as the dominant process in conceptual, or nonmonotonic, change presents a worthy challenge to more established theories, such as Chi's theory of ontological shift. The two approaches differ primarily in that Ohlsson's theory emphasizes a process of learning in which narrower, more specific concepts are subsumed by more general, abstract categories through recognition of similarities, whereas Chi's theory emphasizes the dissociation of overly general categories through the recognition of differences. We examine the evidence for both theories and consider the educational implications of each. Overall, though subsumption almost certainly plays a role in nonmonotonic change, we maintain, on the basis of evidence from cognitive science and developmental psychology, that dissociation accounts for a greater portion of the re-representational processes underpinning changes in the structure of learner's knowledge.

In an impressive undertaking, Ohlsson (2009/this issue) presents a theory of learning that requires abandonment or rejection of prior misconceptions, incorrect beliefs, or intuitive theories. Learning of this sort, in contrast to learning of the knowledge accumulation sort, has been termed "conceptual change" in the literature of developmental, educational, and cognitive psychology (e.g., Carey, 1985; Dole & Sinatra, 1998; Posner, Strike, Hewson, & Gertzog, 1982; Vosniadou, 2008), and Ohlsson uses the term "nonmonotonic change." Chi's (1997, 2005, 2008) theory of categorical shift would be an example of a conceptual change theory.

Conceptual change theories arose to handle the phenomenon of learners having prior incorrect beliefs that are resistant to change. Conceptual change requires learners to abandon their prior conceptual framework because explanations of their framework are inconsistent with and contradict correct scientific explanations. However, when presented with correct explanations, learners have a tendency to assimilate such new information to existing theories and explanations, even when the new information is anomalous. Alternatively, the pull of their own existing theories and explanations is so strong that learners sometimes prefer to discard, distort, or explain away anomalies (Chinn & Brewer, 1993). This rejection is often carried out so thoroughly that it seems impossible for contradictions and inconsistencies to ever reach the crisis level that would bring about conceptual change. In short, whether learners assimilate or reject new information, their existing framework is maintained, thus creating a "learning paradox" (Bereiter, 1985). That is, how can learners possibly learn something new? The goal of conceptual change theories is to understand and propose a way to overcome such stubborn resistance to change, resulting from both assimilation and rejection.

To overcome the problems associated with assimilation or rejection, Ohlsson proposes a process he calls "resubsumption." To overview, resubsumption is the process by which an existing theory is considered to be capable of encompassing and explaining additional experiences or phenomena and can occur prior to any confrontation with anomalies. In Ohlsson's theory of nonmonotonic change, a learner began by developing specific, relatively isolated, informal, or naïve theories for everyday experiences, a process he calls "routine knowledge formation." Then at some point, the learner comes to realize, perhaps accidentally, that an alternative theory could also explain a particular phenomenon, entering a period of "bisociation." The learner weighs the competing theories, and if it becomes clear that this alternative theory is preferable to the other, it will then subsume the phenomenon. Thus, resubsumption occurs without necessarily having confronted anomalies. Instead, how one recognizes the need to generalize

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a theory depends on recognition of similarities. According to Chi's theory, although the initial development of new knowledge does occur in a way similar to Ohlsson's "routine knowledge formation," new knowledge may get embedded in an incorrect hierarchical category. Change is triggered by noticing differences in the phenomena, thereby recognizing (perhaps accidentally or from being told) the explanatory limitation of the existing category, and an alternative or new category, providing a better account, is either activated or created. The process of conceptual change is then brought to fruition by a categorical shift from the original category to the alternative one.

In sum, one gross way to characterize the main differences between Ohlsson's and Chi's theories is to say that in the resubsumption theory, a specific theory is generalized to cover more experiences, whereas in the categorical shift theory, specific experiences need to be differentiated so that it can be explained by an alternative theory. Moreover, how one recognizes the need to generalize a theory or differentiate an experience also differs between the two theories. The resubsumption theory appeals to processes of analogical reasoning, and the categorical shift theory appeals to processes of noticing contrasts.

Ohlsson's (2009/this issue) article is extensive and filled with many important as well as subtle points. This response is necessarily short and so cannot address every aspect of Ohlsson's argument. Three important issues that are omitted here concern (a) why conceptual change occurs with low frequency, (b) whether conceptual change is sudden or gradual, and (c) the relationship between conceptual change and development.

In the following comments, we first discuss key similarities and differences between the two theories in the context of knowledge formation and acquisition, conditions of change, and instructional implications. Then Ohlsson's main criticisms of the categorical shift theory are addressed. Finally, we raise some outstanding issues regarding nonmonotonic change.

COMPARING THE TWO THEORIES

Routine Knowledge Formation and Acquisition

We lay out the resubsumption theory and conceptual shift theory by using the example of learning to correctly understand *whales* as *mammals*. According to both Chi and Ohlsson, it is reasonable that young learners will form intuitive theories based on experience. When they see a big torpedo-shaped swimming creature (a shark), they create a representation of the category *shark*; experience with another group of torpedo-shaped swimming creatures causes them to create the category *whale*. Using the terminology of Ohlsson, these are examples of routine monotonic accumulation.

In Chi's account, these categories of *shark* and *whale* would both be treated as members of a superordinate category such as *fish*, and all of the information the learners have about the structure, function, and behavior of *fish* would be applied to both subcategories. Using Ohlsson's terminologies, one could say that learners use their theory about *fish* to explain the structure, function, and behavior of sharks correctly but whales incorrectly. In Chi's account, the error is made because when two phenomena or domains are similar, then the same theory or category is used to explain them. On the basis of the literature on misconceptions, the categorical shift theory assumes that learners are overly general to start with, and learners are misled by similarity. That is, whales are categorized as *fish* because of their similarity to *fish* and not as *mammal* because of their dissimilarity to other known mammals. In fact, whales can be incorrectly categorized as *fish* regardless of whether a child has the category of *mammal* or not.

According to the resubsumption theory, however, in the initial phase of knowledge formation, learners begin by being overly specific. They formulate a theory for each domain or phenomenon. Experiences with sharks and whales would lead to the construction of separate theories or categories for *shark* and *whale*, and no assimilation to the *fish* category would occur, at least not spontaneously at the time of first gaining experience with sharks and whales.

To take another example, geese flying in a V-formation look very much like pilots flying in a V-formation during an air show. Because the two occurrences look similar, people will invoke the same causal explanations to account for the V-pattern. The lead pilot and the lead goose both instruct the rest of their companions where to fly. This is quite correct in the case of the pilots, but the actual causal explanation for the geese is quite different. There is no leader goose. The pattern of geese flying in a V-formation arises purely from each individual goose doing its own thing, which is to fly where there is the least amount of air resistance. When each goose is following its own goal of drafting, a V-formation naturally emerges. As the lead goose, which does not have the benefit of drafting, tires, it falls behind and a new pattern will emerge with a new leader, but there is no conscious choice of a leader; the change in the pattern as a result of the leader slowing creates a new drafting solution for the individual geese. There is no way for a learner to tell from observing the macrolevel patterns of V-formation this difference between the pilots and the geese, and therefore they apply the same category or theory to both, one involving what Chi (2005) called direct processes, instead of correctly identifying the goose example as exemplifying emergent processes.

Although the goose-and-pilot example comes from Chi's work, Ohlsson provides examples of cases that fit this same pattern of collapsing distinct phenomena as the same, including electromagnetism subsuming optics, variation and selection subsuming aircraft design, and Newtonian mechanics subsuming Boyle's gas law. According to Ohlsson's theory, the learner would form distinct theories for each of these situations initially, then later combine. However, although

some of these resubsumptions do indeed improve the learner's understanding—such as broadening Newtonian mechanics to include electromagnetic theory—others could create misconceptions, such as impeding the understanding of flocking, or muddling cases of intentional variation and selection with cases of random or undirected variation and selection. For example, in the case of aircraft design, by learning about controlling the selection process or introducing variation in the aircraft example, learners may come to believe that all cases of variation and selection are a result of intentional design. They may better understand design but have a worse understanding of natural selection. In short, Ohlsson's theory does not address the issue that collapsing distinct phenomena could lead to misconceptions as well as dispel them.

This maintaining of distinct and specific categories or theories is effective insofar as it allows Ohlsson's theory to avoid the assimilation paradox. It is not that the learners are wrong, really, just that they have not taken their theories as far as they might and therefore have not recognized opportunities for subsumption. But it seems that maintaining distinct specific theories ought to also result in the creation of misconceptions in at least some instances, as previously noted. In contrast, in Chi's and other theories of conceptual change, because the initial formulation of knowledge is overgeneralized, the subsequent focus is on differentiation as the primary direction of knowledge development. Other examples would include the differentiation of heat and temperature or of weight and density, as well as additional cases in which inappropriate analogies are applied, such as that between water and electricity, or artificial breeding and natural selection.

We note, too, that besides subsumption and differentiation there may be a third sort of transformation, in which two theories come together, or coalesce. For example, the unification of the theories of electricity and magnetism was certainly not a case of differentiation, but it was also not a case of subsumption. Electricity did not become an instance of magnetism, or vice versa. Both theories contributed to the final outcome, and the understanding of both phenomena was significantly changed by the coalescence. The same can be said of attempts to reconcile particle and wave theories of light, and the development of chaos theory out of the apparently disparate phenomena of the mixing of fluids, weather patterns, and the growth of biological populations. However, it is not clear that a mechanism such as coalescence characterizes conceptual change in learners; it may be used primarily by scientists.

Conditions for Change

Both Chi and Ohlsson's theories must specify the circumstances or triggering condition under which the process of change is initiated. In the case of resubsumption theory, it is the recognition that a theory constructed for another purpose is relevant and useful to explaining a different phenomenon. Thus, according to Ohlsson, the theories of electromagnetism and optics were joined when it was realized that the phenomena described in classical theories of optics were describing a special case involving visible electromagnetic energy. The resubsumption theory, then, requires learners to notice similarities between two domains through some sort of analogical mapping mechanism. In addition, the focus in resubsumption theory is on an existing theory being entertained as a way of explaining an alternative phenomenon because of the similarities noticed (or pointed out) between the phenomenon that the theory was designed to explain and this new candidate for subsumption. The similarities between other electromagnetic phenomena and those described by classical optics, for example, encourages the learner to consider optical phenomena as covered by the preexisting electromagnetic theory.

In the categorical shift theory, just the opposite assumption is made with respect to the condition that might trigger categorical shift. Because differentiation is the key mechanism, there is a need to ignore similarity and instead to give more weight to detect differences that encourage differentiation. The process of differentiation does not require an existing category, as the learner can decide to exclude a set of things or events from a category without necessarily knowing where to put them. For example, if a child did not have the category *mammal*, this would not stop her from realizing that whales have blowholes instead of gills, give birth to live young instead of laying eggs, and have other differences. It is quite possible for her to decide that whales are not *fish* without knowing they are *mammals*.

It is important to emphasize that a condition can trigger dissatisfaction with an existing category without necessarily having the availability of an alternative category. This assumption makes the conceptual shift theory less vulnerable to the assimilation paradox than Ohlsson suggests, as it does not characterize learners as completely beholden to existing configurations until some equally good or better configuration comes along. Anomalies exist only in the context of a particular theoretical framework, but differences can be quite apparent without being immediately seen as problems or as compelling the learner to resolve them.

In essence, both theories incorporate the concept of a "shift." In Ohlsson's theory, the shift results in a growing cluster of entities and phenomena that can all be explained by the same theory; in Chi's theory the shift creates differentiation into more theories, but both are shifts. Moreover, both theories also propose that the trigger for conceptual change is not a conflict between theory and data, but rather the accumulation of information that eventually triggers a shift. But theories of how an accumulation of information can trigger change do differ. The resubsumption theory appeals to the process of noticing analogical similarities, whereas the categorical shift theory appeals to the process of noticing contrasts.

Instructional Implications

One of the most important issues to be addressed by a theory of conceptual change is how to foster it through instruction. According to Ohlsson (2009/this issue), the two theories imply similar instructional implications, in that both theories "suggest that instruction should begin somewhere else and establish a conceptual structure to which the target subject matter can be assimilated" (p. 37). This is a surprising statement of the instructional implication of his theory, given that in the resubsumption theory, the target theory exists, whereas this is not a prerequisite under the conceptual shift theory.

Ohlsson proposes a displacement strategy as a way to establish an alternative conceptual framework to which learners' existing knowledge could be subsumed. A microworld, games, or other strategies could be used, he suggests, to displace students' attention to a promising alternative. This alternative should be one about which the students do not have strong prior conceptions and that allows them to grasp the important principles. Once accomplished, the instruction would support the transfer process that would complete the subsumption process. An example he gave was to teach principles of variation, reproduction, selection, and accumulation of changes over time in an unfamiliar domain, such as the evolution of bacteria (p. 37). Then, once students have understood the evolution of bacterial populations, support transfer of that understanding to other populations.

It seems that the displacement strategy will face two hurdles. First, Ohlsson (2009/this issue) notes himself that transfer is not something that human beings are particularly good at (p. 37). Moreover, the displacement strategy presupposes that it would be easier to teach these principles in a novel domain. Even if a completely unique environment could be created, such that the learner had no prior knowledge and no similarities could be detected between the artificial world and prior experience, there are cognitive heuristics and biases that we would predict would come into play upon first exposure to this new or artificial world (Evans, 2008; Wellman & Gelman, 1998). In the realm of evolutionary biology, for example, developmental biases toward essentialism (Gelman, 2003), teleological explanations (Kelemen, 1999), and the intentionality constraint (Evans, 2000, 2001), all come into play at a very young age when children are first exposed to new concepts. Other domains would likewise be affected by heuristics and biases. For example, cases from the social domain could be affected by stereotyping, the fundamental attribution error and the outgroup homogeneity bias; situations involving probability judgments will likely be hampered by base rate neglect, anchoring, and confirmation bias. Thus, it seems unlikely that a truly novel domain will be found.

From the perspective of categorical shift theory, instruction can be described as having three phases. First, we teach students how to differentiate between domains of phenomena. For example, we might teach students the characteristics that will allow them to identify emergent causal processes and direct causal processes (such as the autonomy of individual agents, the uniformity of the rules and procedures followed by the agents, and so forth). Next, we explain that there are two theories, and how they are different, using contrasts rather than analogies. In particular, we teach the alternative structure as a qualitative, generic, schemalike structure. In this case, that would mean teaching an emergence framework which is not specific to, say, geese flying, but to a wide range of emergent phenomena. Once established, this generic qualitative structure allows students to assimilate instruction about the specific phenomena to the structure. Thus, we are in fact taking advantage of the assimilation paradox. We have worked extensively on designing a generic instructional module to teach ideas about emergence, creating a generic instruction module, then applying it to other emergent phenomena such as diffusion, and evaluating with a different emergent process, such as heat transfer (see details in Chi, Roscoe, Slotta, Roy, & Chase, 2009).

Our instructional technique uses an approach that is the opposite of that proposed by Ohlsson. We teach a new domain-general category by contrast, overcoming similarity, rather than using similarity to bring about change. The implication is that, unlike the resubsumption theory that requires only analogy, ours posits that to create new ideas and new categories, learning by contrast may enable conceptual change. Moreover, learning by contrast may be an easier mechanism for learners to implement because they need only to notice differences between external phenomena or experiences, instead of the usual instructional mechanism of asking them to resolve anomalies that contradict their intuitive theories for which they are strongly committed. Thus, our approach may bypass the learning paradox.

RESPONSES TO ADDITIONAL CRITIQUES BY OHLSSON

Ohlsson levels three criticisms at the categorical shift theory. First, he claims that it focuses on ontological knowledge as opposed to treating all knowledge the same, as the resubsumption theory does. Second, it does not specify a triggering condition for when conceptual shift occurs. Finally, he takes issue with the way that cognitive load is raised by the categorical shift theory.

Ontologies

Essentially, there is no disagreement here. Although some categories might be ontological, the categorical shift theory does not have to convey special status to some categories over others; the issue is left as a philosophical issue regarding epistemological status. Instead, categorical shift theory can make sense by stating that any lateral shift is an important conceptual change event.

However, there are two caveats. First, it seems that there still may be some unique status to the highest fundamental categories, such as entities/matter, processes, and mental states. Even Ohlsson (2009/this issue) implies their importance when he states that "matter either does or does not occupy a given region of space" (p. 27). Second, what may seem like trivial shifts from one person's perspective may be ontologically significant from another. For example, using Ohlsson's examples, it seems that the shift between a natural apple to an artificial apple can be carried out matter-of-factly by adults, as his example portrayed (p. 33). But the distinction between natural kinds and artifacts is not trivial for a 3-year-old (Gelman & Markman, 1986). For an adult or older child who has already made this realization, recognizing an artificial apple may seem trivial but that does not mean that there is no ontological significance, just that this particular hurdle has already been overcome.

Trigger Conditions

Ohlsson's second criticism is that the categorical shift theory does not specify a triggering condition for when conceptual shift occurs, other than to state that conceptual shift is difficult because learners do not necessarily realize when it is necessary, or they may not yet have the category into which the shift is needed. We do hedge on specifying a trigger condition precisely because it has been difficult to detect such triggers empirically, as would be expected and consistent with the lack of evidence for conceptual change in the literature. However, we can lay out our hypotheses concerning the circumstances under which a shift would be initiated.

In cases in which the alternative category exists, then the triggering conditions would likely manifest as or around the identification of a difference. The learners could recognize a feature they had not noticed before, either spontaneously or by having it pointed out. In cases of tenacious misconceptions, those that are difficult to suppress, remove, or change, not only would noticing differences be required but the construction of the alternative category would also be necessary.

The resubsumption theory claims that conceptual change is triggered by a conflict between theories. However, the important role of conflicts between two theories or between theory and data might be more appropriate for describing conflicts encountered by scientists. This point is also made by Ohlsson (2009/this issue), who claims that one can make "too much of the relation between individual cognitive change and scientific theory change. Although theory change requires that some scientists undergo a change of mind, the two cannot be equated" (p. 34). Scientists, he goes on, have the goal "to evaluate evidence and arguments. The cognitive utility of the theories they use is therefore determined by the power of the latter to generate accurate explanations and predictions" (p. 34). In contrast, we claim, the very problem that learners face is that they do not have multiple theories to rely upon. In addition to the first problem that Ohlsson touched upon, that people are not engaged in scientific activity as they go about everyday life, they are also unlikely to generate two distinct theories for similar-looking phenomena.

Cognitive Load

The third criticism has to do with a passing comment Chi (2005) made about the cognitive demand of reinheriting all the attributes of a concept based on its new category membership, once the concept has been reassigned. This cognitive demand issue pertains to processes that occur after a conceptual change has taken place, it is not an explanation for the rarity of the conceptual shift and is thus secondary to the issues of triggering conditions and frequency of shifts.

CONCLUSIONS

Ohlsson offers a noteworthy challenge to conceptual change theorists and does make a good case that resubsumption may be the mechanism in some cases of nonmonotonic changes to a person's knowledge base. However, we believe that the case against other mechanisms of change may be overstated, based on some developmental findings. For example, there is a robust empirical literature documenting developmental instances of differentiation and historical instances of coalescence, suggesting that resubsumption is one amongst several mechanisms whose relative power in explaining learning has yet to be parceled out. Moreover, there are findings in the developmental literature that suggest that some realizations he posits as trivial (e.g., the artificial apple) may only be trivial after reaching significant developmental milestones, whereas others (e.g., finding a novel domain in which to teach natural selection) may be quite challenging because of strong developmental biases that persist into adulthood. In these cases, the use of contrasts may provide learning opportunities that displacement would not.

Although we basically agree that anomaly detection is not necessarily a triggering condition for conceptual change, it is worth noting that anomaly detection need not be "all or nothing." Whether anomalies are detected as contradictory and inconsistent depends on the learners' knowledge and motivation. In the most extreme cases, when learners possess an extreme level of commitment to their current theories, they may be oblivious to anomalies and conceptual change would not occur. However, there is undoubtedly a great deal of variance in the degree to which learners have confidence in their theories, their level of emotional attachment to them and to being right, how available those theories are in memory, how cognitively penetrable and open to metacognitive evaluation they are, and so on. If their commitment is more modest, they may notice differences on their own, with some differences eventually being recognized as problematic (such as a lack of gills), and others not (a 700-lb bluefin tuna is still a fish, even if it is 1,000 times larger than any fish the child has ever seen

before). In short, learners' receptiveness to anomalies will vary with their level of commitment. Thus, it seems reasonable to propose that the "learning paradox" exists only in a subset of cases in which nonmonotonic change is needed and that, although perhaps never easy, is not always as seemingly impossible as suggested. Moreover, the role of contrasts in triggering conceptual change provides a mechanism that is not as vulnerable as anomalies to this problem of "learning paradox," as contrasts are not inherently shortcomings that must be explained away.

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