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Metacognition as A Predictor of Conceptual Change

Abstract

Metacognitive ability- proficiency in analyzing ones own thought processes - is related to the ability to correctly gauge one's mastery of a task (Kruger, 1999; Dunning, 2003). It may also be tied to the ability to make radical conceptual changes - learning new information incongruous with prior beliefs. We hypothesize performance on an expanded version of the Cognitive Reflection Test (Frederick, 2005), a battery of questions designed to measure metacognitive ability, would be a predictor of the extent to which undergraduate college students (N=103) improved their understanding of evolution after a semester of college level biology, particularly in the Darwinian principles behind natural selection such as inheritance, variation, and superfecundity. The benefits should be most pronounced in subjects displaying greater metacognitive ability whose prior knowledge incorporated flawed beliefs such as LeMarckianism or needs-based evolution. If metacognitive ability is indeed predictive of learning, it would suggest conceptual change is facilitated by a disposition to think about one's own concepts. It would also suggest that the quality of education in fields such as biology may be improved by fostering and encouraging more reflective thinking.

Introduction

In most classrooms, there are one or more students who behave qualitatively differently than their peers. Regarded as 'quick on the uptake' or other such terms, much effort has been put into understanding what distinguishes them from their peers and whether similar techniques can be taught to other students in order to improve their performance. This paper focuses on the role of metacognition as a possible factor in the ability to learn; primarily because there are several studies relating learning to metacognition. While research into the specific mechanism by which metacognition plays its role in learning remains inconclusive (Cull, 1994), the two processes are so strongly linked that in a recent literature review on metacognition it has been stated no less explicitly than "In memory research, metacognition was invoked to account for the ability of subjects to strategically control their learning," (Fleming, et al., 2012). Metacognitive ability- the ability to reflect on one's own thought processes- has previously been correlated with the ability to monitor one's own performance

accurately; one possible explanation for its role in learning ability. The Dunning-Kruger Effect is a famous example of metacognition research: Dunning and Kruger found that most people consider themselves above average in a variety of fields; for example, Kruger found that participants in the twelfth percentile of various tests on humor, logic, and grammar believed themselves to be of the 62nd percentile, while Dunning later asked psychology students for their self-assessment on their perceived mastery of the material before a test and their projected score afterwards, finding a similar effect; most participants considering themselves to be somewhere in the 60th percentile, while the top percentile was much more accurate in its self-assessment. (Dunning, 2003; Kruger, 1999) Whatever process enables the high-achieving students to accurately gauge their own performance, it is clear the average low-achieving student has less aptitude for it.

This, once more, leads to the implication that metacognition is correlated with the ability to learn; for example, it has been noted that metacognition influences learning strategies *similarly* between both good and poor learners in tasks of metamemory (Cull, 1994). At this point, it becomes necessary to make a distinction between two types of knowledge acquisition: *knowledge enrichment* and *conceptual change*. Human cognition is guided by collections of domain-specific knowledge (Carey, 1994). These domains encompass various fields in which humans must reason; such as numeracy. Numeracy constitutes the ability to recognize numbers, and perform operations upon them based off of our understanding that unique numbers have some shared properties in which individual numbers vary. One core principle that is acquired early in the building of numeracy is the principle of succession which postulates any two unique numbers can be compared and an unequivocal conclusion can be reached in regards to which is greater or lesser, often analogized to children via the concept of a 'number line'. Literacy, similarly, consists of acquiring principles such as written syntax, the distinction between verbs, adjectives, and nouns, and the principle of tense as a modifier which can be applied to verbs. A distinction can be drawn between two domains if the core principles upon which they rely are different; for example, the principle of 'succession' cannot be applied to language as it is in mathematics, e.g. the word 'cow' cannot be called either greater or lesser than the word 'chair'.

Within these domains, once sufficient knowledge has been gathered with which to construct these core principles, additional knowledge may be acquired which is *not* a new core principle, but simply a permutation that fits within the existing knowledge structure. For example, learning a new word is an example of enrichment of a previously existing domain-specific knowledge. Even the acquisition of a new language can be classified as knowledge enrichment, as many languages rely on the same core principles such as syntax. As a knowledge domain becomes further enriched, the concepts underlying one's understanding of the domain similarly become further entrenched. On the other hand, conceptual change is invoked when one realizes that an essential core principle of domain-specific knowledge is incorrect. Examples of this change with regards to the field of biology will be discussed further on.

The role of metacognition in respect to metamemory has been previously studied, often with tasks such as the ease-of-learning (EOL, the reported difficulty with which participants expect from a task) and the judgment-of-learning (JOL, the self-assessment of whether or not a participant has sufficiently learned a subject). Ease-of-learning and judgement-of-learning are metacognitive tasks, requiring the subject to gauge his or her own capability at a task. In order to judge if a fact is difficult or easy to retain, participants must have some self-awareness of their own learning process; at the same time, in order to judge whether or not they have accurately mastered material, the participants must have some self-awareness regarding what they have and have not learned. Metacognition is linked to knowledge enrichment in metamemory tests; both poor learners and good learners modify their study habits on later memorization tasks according to their EOL judgments. These ease-of-learning judgments are *positively* correlated with the time spent studying an item, suggesting metacognition plays a role in allowing for optimal resource allocation while learning. The role of metacognition in learning is so taken for granted, in an article that similar finds judgments are made between good and poor learners regarding study time allocation and EOL, the possibility of an alternate hypothesis- that of metacognition being unrelated to learning- is expressed, but nearly immediately rejected. (Cull, 1994)

The authors instead take their own results with a grain of salt: “[In reference to rejecting metacognition's role in learning:]*Such a position is contradicted, however, by a number of other studies indicating that a relationship between metacognition and learning ability does exist. These studies show...that adults make better metacognitive decisions than do children... more successful fifth graders monitor learning difficulty of prose passages better than do less successful fifth graders...high-achieving college students more accurately discriminate what is known and not known than do low-achieving students... college students who perform better on a text comprehension task monitor their comprehension better than students performing less well... even that expert memorizers regulate study more effectively than do novice memorizers(see Intons-Peterson & Smyth, 1987).*” Cull notes an interesting observation: “*Studies that have revealed a relationship between cognitive monitoring and learning ability generally have used tasks and materials that are more complex than those used in studies not revealing a relationship.*”

A notable feature shared amongst these tasks, however, is that JOL and EOL in specific and metamemory tasks in general measure only *knowledge enrichment* because they generally involve the participant memorizing words. Thus there is a growing body of knowledge on the interactions between metacognition and knowledge enrichment, but proportionately less research into the role of metacognition in conceptual change. If the observation hinted at by Cull is true - that more difficult tasks are the ones in which metacognition plays a greater role - then conceptual change, which is a learning task of greater difficulty, should show an even stronger relationship between metacognitive aptitude and learning.

Earlier, we drew a distinction between conceptual change and knowledge enrichment with the understanding of later discussion of certain specific conceptual changes in the field of biology. (Shtulman, 2006) Early in life (up until between six and nine years of age) children have a variety of misconceptions on the nature of biology, in which an intuitive explanation is posited for phenomena such as inheritance. When asked about the heritability of certain traits; for argument's sake, the trait of having blue eyes and the trait of being educated. Preschool children are capable of recognizing that children will often take after their parents, but they fail to draw

distinction between the former, which is a function of genetics, and the latter, which is a function of exposure to educated parents (Carey, 1994). Between the ages of six and nine, they stop giving the intuitive, nonmechanistic answer which fails to distinguish a genetic adaptation from an adaptation made by an organism within its lifetime. The reason for this is because almost all children make a conceptual change in their understanding of biology at around this age: they become acquainted with the concept of *birth* as the means by which parents produce offspring. This provides an explanation for the similarities between parents and children which simply sharing an environment can not explain; because of this conceptual change children become capable of inhibiting their intuitive response, the fallacy in which children overgeneralize their own *context-based experiences* to the biological function of heritability. Instead, they begin to espouse a mechanistic view where biological traits are inherited via birth and cannot simply be learned through effort. Interestingly, not all intuitive responses universally wither away with age. It has been noted that some incorrect core principles are still capable of coexisting with correct ones, oftentimes for years. (Shtulman & Valcarcel, 2011) Why, then, are people so resistant to throwing out prior conceptions? Dual process theory, in particular the theory of cognitive miserism, provides a satisfactory explanation. Dual process theory is articulated as followed: “*Although relatively new to developmental theorizing, dual-process theories are prevalent... Dual-process theories propose that multiple independent but interacting processing systems underlie thought, judgment, and decision-making.*” (Amsel, 2008) The claim is that there are two distinct processes which govern cognition; intuition and analysis. (Kahneman & Frederick, 2002)

Generally, the difference between the two processes is one of *cognitive economy*; that is to say, one of the processes provides immediate, reflexive responses that are formed not through analysis but by the prior sum of experiences and context-rich situations. This results in heuristic-based reasoning that, while generally useful, can lead to mistaken beliefs because this process relies not on formal reasoning but more upon emotional responses as well as concrete representations of a task. Thus, this system is suitable for coming to quick conclusions- everyone leaving the office for their lunch break is bringing their umbrellas with them, and prior experience states

that this usually entails rain. This process of intuition is enforced by knowledge enrichment within a domain; as stated above, knowledge enrichment in the form of experience enforces existing conceptual principles, further predisposing us towards our own natural intuitive responses. However, as far back as David Hume it has been noted that inductive reasoning relies on our limited experiences of the world in order to make predictions about the world at large. An example of knowledge enrichment *miscalibrating* cognitive heuristics can be found in racial stereotyping: because most media reports on violent crime feature minorities, experience via a lifetime of violence-related news reports leads to many instances in which an individual can draw upon a large body of context portraying minorities in a negative light. A result of having this *context rich* experience, misperceptions about minorities as a whole may arise and an intuitive suspicion towards minorities may develop in the form of racism; leading to incorrect conclusions about individuals.

Analytical reasoning, on the other hand, is cognitively effortful. Analytical reasoning tends to be deductive, although probabilistic inferences may be reached through analysis and yet still have some margin for error (For example, analytical thinking states that *very few* individuals of a minority ethnic group are actually involved in violent crimes; thus there is no more reason to fear a young black man more so than a young white one. Specific instances of minorities committing crimes do not disprove the analytic validity of the prior statement; nor does the prior statement preclude the possibility of minorities committing crimes: here probabilistic analytical thinking simply results in an inference).

The utility of analytical reasoning lies in all of the respects in which it is the inverse of intuitive-experiential reasoning: because it functions *out of context*, it enables humans to make conclusions about unfamiliar systems. This knowledge process will work for a variety of situations; without prior experience or knowledge of a subject, enabling us to operate in novel situations as long as the premises upon which it is based hold true. Because this process is cognitively effortful, we generally rely upon empirical, intuitive/experience-based reasoning where we use prior examples to justify our responses. The more context one has, the more likely one is to use intuitive

processes over analytical ones. Because these intuitive responses are not eliminated by either age or education, there is a suggestion that there are two separate systems rather than one which continually refines itself towards increasing formality and systematicity. (Amsel, 2008)

The question rises, then, with regard to what process produces the switch to analysis instead of relying upon intuition. An obvious candidate is metacognition; for example, feeling-of-rightness is one strategy which prompts additional analysis (Thompson, et al., 2011). While not the focus of this paper, there are neural correlates of feeling-of-rightness, notable mostly as a reduction in the P400 response of neurons which signals the need for further analysis (Reid, 2008). Upon reflection, various other metacognitive strategies exist to prompt further inspection of a phenomenon behaving inconsistently with previous conceptions of it; suggesting that metacognition has a direct role in dual process theory at the cellular level.

If conceptual change is a complex learning task which involves actively inhibiting previously acquired knowledge and the intuitive conclusions it leads to, and metacognition is implicated as the agent which overrides this intuitive process by engaging analysis, one possible conclusion is that measuring metacognitive proficiency by examining a propensity towards analysis over intuitive thinking may be able to predict which subjects make conceptual changes. As mentioned above, biology is a field in which there are robust misconceptions which may be observed across a wide pool of subjects. (Shtulman, 2006; Carey, 1994). The intuitive misunderstanding of the nature of heritability is only one of many *mis*-intuitions regarding a Darwinian understanding of evolution that experience further entrenches. Life experience provides many contexts in which *individual* organisms may be observed adapting over the course of their lifetimes to more successfully navigate their environments and achieve goals such as food acquisition and reproduction; this leads to misunderstandings when the theory of evolution is later taught. Evolution, as correctly described by Charles Darwin, has three core principles: Variation and heritability, or the concept that individual members of a species *naturally* and *randomly* vary around the mean of

their parents in regards to any trait, superfecundity, or the concept that more organisms are born than their environment can support, and natural selection, the concept that an environment by its very nature allows for certain permutations of a trait to be more successful than others. These three concepts (four if variation and heritability are considered separately), along with other lesser ones such as 'acquired traits are not inherited', make up the current understanding of evolution as the origin of species. A combination of these concepts results in the conclusion that within a species, there are many traits which crop up randomly through processes such as mutation, and the environment naturally allows for certain members of a species with more beneficial variations to reproduce more successfully and thus, their offspring inherit these successful traits until only offspring with these traits may interbreed, whether due to preference, geographic isolation, or genetic incompatibility: thus, the origin of species. The conceptual change that occurs in young children allowing them to understand the distinction between inherited traits and acquired ones centers around the knowledge that birth is essential to the heritability of certain traits. However, before this change, there exists a transformationist misunderstanding which comes from flawed applications of real-world contextual experiences to the theory of evolution, resulting in a nonmechanistic interpretation. More subtle views in the same vein persist in adults; these conceptions are collectively referred to as 'folk biology' and often impede an understanding of evolution. These transformational understandings of evolution are generally based on a lack of understanding of one or more of the above principles, and are often the result of ecological context. As individuals rarely see death, much less that of an entire species, and people acquire adaptations over the course of their lives, it is common to encounter individuals who espouse anagenesis, where individual species do not branch but instead chain into each other; or Lamarckian beliefs where acquired traits are conflated with heritable traits. An example of the former is the common belief that humans are descended from chimpanzees; a lack of comprehension regarding extinction results in the inability to understand cladogenesis. Instead of understanding humans and chimpanzees as agents who eventually resulted in the extinction of our parent species, the assumption is that since the chimp is our genetic next-of-kin it must be our ancestor; this misunderstanding is intimately tied to the belief that humans are somehow 'more evolved', 'not animals' and other beliefs mistakenly attributing distinctions between *Homo sapiens* and all

other living beings. A lack of understanding regarding heritability, and the distinction between within-organism and within-species adaptation, results in beliefs such as 'successive generations of giraffes stretched their necks' in the same way that an athlete may practice for an event.

Based off of the existing body of literature, we project that metacognitive ability may serve as an accurate predictor of whether or not subjects are able to effectively supplant an intuitive, transformational theory of evolution with an analytical, variational theory of evolution. Due to the previous implication of metacognition in comparatively more complex tasks of knowledge enrichment (Cull, 1994), we wished to investigate the role of metacognition in achieving conceptual change - a task of arguably greater complexity than knowledge enrichment.

Methods

Experimental Design

In order to test the effect of metacognition on the ability to make conceptual changes, we gauged metacognitive ability and understanding of evolution using a battery of questions easily answered by analysis but designed to elicit incorrect intuitive responses from participants. Then, subjects took a course on evolution, and given the evolutionary understanding again; the purpose of which is to note any interaction between metacognitive performance pre-instruction and conceptual change between transformational and variational theories post-instruction.

Participants:

Participants were selected from a pool of undergraduate students taking a biology course at the University of Massachusetts - Boston (n = 103).

Materials:

The Cognitive Reflection Task (CRT):

We believe that metacognition plays a role when there is conflict between analysis and intuition; to this a battery of questions were used to prompt a 'prepotent' response. This is a response in which the intuitive answer seems both very obvious and is, upon even the slightest analysis, incorrect. Unlike other general measures of problem solving, the dichotomy between the correct, analytic responses and the incorrect, intuitive responses allows for an easy measure of not general intelligence but metacognitive performance in specific. Originally devised to be three questions long (Frederick, 2005), the CRT was lengthened to five questions in our study in order to better match the evolutionary understanding survey, which consisted of six sections of five questions each.

Evolutionary Understanding Survey

Consisting of six sections designed to judge the understanding of the concepts behind variation, inheritance, adaptation, domestication, and speciation, the purpose of this test is to elicit a bimodal response between variational and transformational responses. Some questions were multiple choice; in open ended response questions a team of coders worked to classify variational responses as 1, transformational responses as -1, and ambiguous responses, responses difficult to classify, and poorly articulated responses received a 0. Common transformational answers explained evolution with mechanisms implying intentionality, anagenesis, or other misunderstandings that set them apart. Four coders were used; each of whom coded the responses separately. Then, results were compared and debated in a group setting to determine the final coding of each response; this involved the coding of a total of 14 open ended responses per participant, twice for pre- and post-instruction conditions, for a total of 2,884 open ended responses. Pre-debate between-coder agreement was comparable to other similar literature, hovering between 60 and 90 percent. Between-coder agreement post-debate was in the high nineties for every open ended response.

Results

We achieved a good spread of results; with the CRT scores achieving a full range of zero to five correct responses and the evolutionary understanding survey pre-instruction condition having a range of -24 to 24 and a post-instruction condition having a range of -23 to 28; mean CRT score was 1.79 correct answers while mean pre- and post- instruction evolutionary understanding scores were -5.92 and -2.50, respectively. What jumps out immediately is that the minimum understanding rose, the maximum rose, and the mean rose; implying instruction is useful in accomplishing conceptual change. The difference between pre- and post- instruction score was, on average, 3.43, with a maximum decrease of 11 points and a maximum increase of 21 points; suggesting that the benefit of instruction in achieving conceptual change outweighs the risk of entrenching existing concepts.

Metacognitive ability was a moderate predictor of performance in the pre-instruction condition; with a correlation of .286 ($p = .004$). Below is a graph showing which specific fields metacognition initially provided a protective effect in; significant effects are in lighter bars while the areas of variation and speciation did not have significant correlations between CRT score and pre-instructional scores.

While not all of the concepts within the evolutionary survey were significant, the majority were and all of the correlations point towards a positive effect of metacognition on the willingness to engage in analytical thought. The least significant, lowest pre-test correlations were between Speciation and Variance and correct CRT scores; everything else was significantly correlated at at least modestly. On the other hand, the only significant ($p < .1$, a very generous measure of significance) post-instruction correlations between CRT score and improvements were noted in these areas of speciation and variance. Additionally, in an analysis of variance regression, when total pre-instructional score was held as normal, this explained 8.6% of the variation in total change in score. On the other hand, CRT results predicted another 19.5% of the variation in change in score.

Discussion

Due to the positivity and significance of our correlations, metacognition has been strongly implicated in the ability to make conceptual change, with CRT score as a measure of metacognition and evolutionary understanding in

terms of variationism as a measure of conceptual change. Possible objections to this conclusion may claim that the CRT is a measure of general intelligence more than metacognition, or that because intuitive prepotent responses are prompted in both the CRT and evolutionary understanding survey, students resistant to being misled by intuition will naturally perform better on both measures. The response to the first objection lies in the nature of the CRT questions: while other measures of general intelligence generally require one to engage in analysis without any easy, attractive alternative such as employing intuition, the CRT is specifically designed to prompt prepotent responses that *only metacognitive intervention can stifle*. In other measures of general intelligence, correct responses may require more intelligence to respond to quickly- in the CRT, engaging in any act of metacognition or analysis is tantamount to coming to the correct response because the problems are not *difficult* once the obvious need for analysis is presented. The second objection, that an underlying system determines competence in both CRT and evolutionary understanding surveys, has a kernel of validity to it: general intelligence *does* imply a better performance on either of these two tasks, and the ability to inhibit intuitive obvious responses provides a massive advantage on both tasks. However, *most* scientific discovery consists of inhibiting intuitive response and *instead* engaging in analysis: for example, the switch from geocentric models of astronomy to heliocentric ones required a discounting of the intuitive context of daily visual experience: the sun clearly appears to go around the earth. However, I argue the same ability to reframe perspective and understand why the sun appears to rotate around us is the same ability to question previous evolutionary theories is the same ability to perform better than average on the CRT. I have been discussing this ability throughout this paper; it's called metacognition. While metacognition was shown to be a predictor of preinstructional evolutionary understanding, it was a stronger indicator *post instruction*: this means that metacognition was responsible not only for some initial protective effect on the evolutionary misconceptions but it still has an active role in *changing* these misconceptions. My data supports this because the areas in which metacognition provided the least drive towards analytic thinking preinstruction are the areas in which metacognition is most useful predictor of conceptual change: not only is metacognition useful in initially avoiding an intuitive answer, metacognition is useful in instantiating conceptual change towards analytical measures of thinking where there was no prior

predisposition.

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Appendix

The Evolutionary Understanding survey may be found at faculty.oxy.edu/shtulman/bio

The five CRT questions are listed below:

1. A bat and a ball cost \$110 in total. The bat costs \$100 more than the ball. How much does the ball cost?
2. If it takes 5 machines 5 minutes to make 5 widgets, how long would it take 100 machines to make 100 widgets?
3. In a lake, there is a patch of lily pads. Every day, the patch doubles in size. If it takes 48 days for the patch to cover the entire lake, how long would it take for the patch to cover half of the lake?
4. A house contains a living room and a den that are perfectly square. The living room has 4 times the square footage of the den. If the walls in the den are 10 feet long, how long are the walls in the living room?
5. A store owner reduced the price of a \$100 pair of shoes by 10 percent. A week later, he reduced the price of the shoes by another 10 percent. How much do the shoes cost now?

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