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Decentralized thinking and understanding of evolution in K-12 evolution education

Anthony J Petrosino[1*], Margaret M Lucero[2] and Michele J Mann[1]

Abstract

Background: Previous work found four areas critical to understanding evolution: variation, selection, inheritance, and deep time.

Methods: An exploratory qualitative approach was taken with a variety of data sources from a larger data corpus. Data were analyzed for emphasis of either decentralized or centralized thinking. Data were analyzed and discussed exploring how a group of high school biology teachers from the same department taught evolutionary concepts.

Results: The paper presents evidence that demonstrates a common lack of thinking from this perspective or incorrectly thinking that evolutionary processes are “driven” by some centralized force.

Conclusions: We now identify a critical fifth component: decentralized mindset or thinking of evolution as a complex system. Possibilities of how this new area can affect learning about evolution are discussed and implications for assessment are also discussed.

Keywords: Decentralized; Complex systems; Evolution; Cognition; Teachers; High school biology

Background

We have begun to see emerging evidence and increasing interest from the social and technological sciences in the concept of decentralized systems. In cognitive psychology and the learning sciences we have seen a gradual but steady shift from individual cognition and individual differences research to research that focuses on distributed cognition and distributed expertise (Bruer 1993; White and Pagurek 1998; Bransford et al. 2000). In technological areas such as the Internet, communication networks (White and Pagurek 1998; White et al. 1998) and robotics (Beni and Wang 1993; Beni 2005) systems are now decentralized and designed to mimic collective behavior.

According to some (Casti 1994; Resnick 1996, 1997; Wilensky and Resnick 1999; Chi, 2005), it is apparent that at some base level, humans have an almost intuitive connection to centralized ways of thinking. To some, humans are pattern makers (Resnick, 1996). When we notice events in the world, we instinctively attempt to create a pattern or a rule, and we often attribute it to some type of centralized control (Jacobson 2001). The problem of course is that sometimes this centralized control does not exist.

Take the example of swarming behavior. Swarming is a collective behavior that occurs by animals of similar size that aggregate together and move together in some direction. This behavior often occurs during migration, but not always. In fact, this type of behavior is found throughout nature, sometimes using different terms and referencing different organisms, such as flocking (birds), herding (quadrupeds), schooling (fish), blooms (phytoplankton) and even cancer cells (Deisboeck and Couzin 2009). Taken as a larger class, swarming is an emergent behavior arising from some fairly simple rules followed by individuals and does not involve any central coordination Researchers have created models of swarm behavior by programming individuals to maintain personal space while turning and moving in the same direction as others (see Couzin and Krause 2003 for a full discussion on modeling self organization and collective behavior among vertabrates). Another example of modeling is using agent-based computer programming that is able to model decentralized systems where local interactions produce emergent behaviors such as gas-molecule distribution (Wilensky and Resnick 1999; Wilensky and Stroup 2002; Wilensky 2003), slime-mold behavior (Wilensky and

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* Correspondence: ajpetrosino@austin.utexas.edu
[1]Department of Curriculum and Instruction, The University of Texas at Austin, 1 University Station D5700, Austin, TX 78712, USA
Full list of author information is available at the end of the article

Resnick 1999), and predator–prey interactions (Wilensky and Resnick 1999).

This assumption of centralized control, a phenomenon Resnick (1997) referred to as the centralized mindset, is not just a misconception of the scientifically naïve. This mindset seems to affect the thinking of nearly everyone and appears to be almost intuitive, especially because many individuals view centralized activities as having a purpose or goal (Jacobson 2001). When examining an ant colony or beehive behavior, we think that the insects are driven by "thinking" about a particular goal such as feeding their young or finding a new home. However, it becomes apparent that these organisms are "responding to environmental cues and internal signals, acquired over their evolutionary history" (Evans 2008, p. 270). Evans (2008) further argued that such goal-directed behavior (and the related centralized mindset) was important in human evolutionary history, in that our survival depended on the detection of other organisms' purposeful behavior as a sign of life, and such signals could have indicated potential danger or a food source to early humans. We can speculate with some certainty that as early humans observed a rock plunging down the side of a mountain, they would have clearly looked for something that might have pushed it, instead of thinking that the rock might have fallen due to the shifting of other nearby rocks on the mountain.

It has not been too many years since most scientists assumed that bird flocks must have leaders (Curtis, 1972). Only with the work of Reynolds (1987) and Heppner and Grenander (1990) have scientists revised their theories concerning flocking behavior. For example, in the introductory biology textbook, *Invitation to Biology* (Curtis, 1972), flocking was described as an infectious behavior with a leader who worked the hardest. Flocking is not mentioned in current introductory biology textbooks but is mentioned in the textbook *An Introduction to Animal Behaviour* (Manning and Dawkins 2012), where it is described as individuals responding to the behavior of other individuals in the group. A similar type of bias in assuming central control can be seen throughout the early history of science.

A classic example, of course, is the assumption that birds in a flock are engaged in a kind of "follow-the-leader" type of game in which the leader (or the fittest) leads the flock to some destination. However, we are now sure this is not the case. Moreover, research has indicated that birds tend to follow rules much more than they follow leaders. The rules for individuals in the flock create the collective behavior (Partridge 1982; Potts 1984; Ballerini et al. 2008). Emergent from this rule-based behavior are flock patterns and simple interactions between the birds, which can be easily modeled in various programming languages (Reynolds 1987; Heppner and Grenander 1990; Couzin et al. 2002; Grégoire and Chaté 2004). The most salient feature, and surprise to most people, is that there is no leader at all—or as Resnick (1996) stated, "Organized without an organizer, coordinated without a coordinator" (p. 1). Despite this collective evidence, most people still assume the explanation of a leader bird for the flocking behavior of birds.

We posit that an acknowledgement and understanding of decentralized thinking is necessary to understand an abstract process like evolution. Because of evolution's perceived complexity, many individuals argue that such a complex process must have some sort of central "drive" or control and that elements of randomness and chance (e.g., mutations occurring) have little part in such a process. Much of the confusion about teaching evolution revolves around specific evolutionary misconceptions (such as those mentioned above), which prevent the accurate understanding of evolutionary knowledge into an integrated whole. In fact, evolution centers on two important processes. One process is genetic drift that is random or stochastic and the other process is natural selection that is deterministic. Understanding evolution means understanding the interplay between natural selection and genetic drift. However, neither process is centrally controlled by a "higher power" but instead locally reacting to environmental fluctuations. Evolution then is a mixture of both types of processes and understanding these characteristics is essential to understanding evolution. Previous work (Bishop and Anderson, 1990; Anderson et al. 2002; McVaugh et al. 2011; Lehrer and Schauble 2012) described the core ideas of variation, selection, inheritance, and deep time as all being essential to integrate within a kindergarten through undergraduate college (K-16) biology curriculum in order to obtain a deeper conceptual understanding of evolution. The current work describes the proposed addition of decentralized thinking to an existing framework (McVaugh et al. 2011) and illuminates instances where a lack of understanding of decentralized thinking is apparent in classroom instruction. Evidence is provided for an argument as to why the inclusion of a decentralized mindset is necessary for integration within a cohesive biology curriculum.

Literature review

In earlier work (McVaugh et al. 2011), we proposed four core areas of critical importance for understanding the concept of evolution—variation, selection, inheritance, and deep time—all of which present challenges to understanding evolution. We propose adding a fifth component: a decentralized mindset (see Figure 1).

It is worth examining the nature of the centralized mindset. Given what we currently know, the widespread acceptance of the centralized mindset might seem surprising. Until the 1800s, almost everyone embraced the idea that living systems were designed by some God-like entity. Even scientists were convinced by the argument from design or the so-called "watchmaker argument" initially

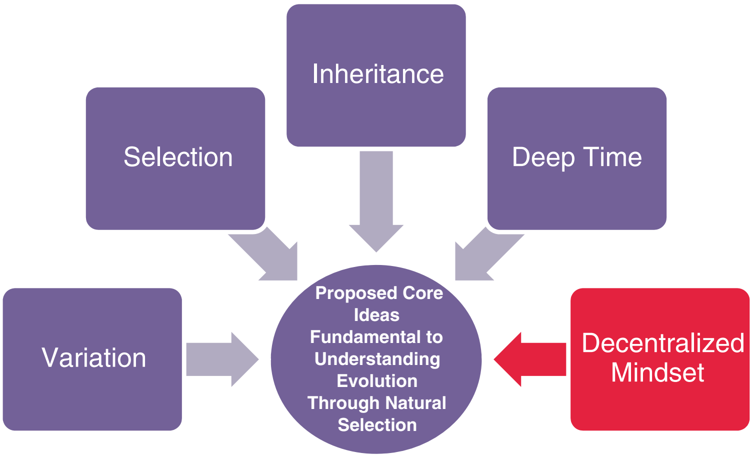

Figure 1 **Core ideas to understanding evolution, with proposed addition of *decentralized mindset*.**

proposed by theologian Paley (1972). Paley noted that watches are very complex and precise objects. For instance, if we found a watch "on a heath" (p.1, 1802 edition), we could not possibly believe that such a complex object had been created by chance. Rather, we would naturally conclude that the device must have had some type of designer or maker. For Paley, a similar logic applied to living systems. It is currently argued that eye and flagellum development are examples of an irreducibly complex structure due to convoluted parts (Behe 1996). How could such complex systems simply emerge or evolve?

It is not surprising that scientists and everyday people accepted Paley (1972) argument in the early 19th century, since there were no viable alternative explanations for the complexity of living systems. What is notable is how strongly scientists held onto centralized beliefs even after Charles Darwin (1859) provided a viable (and more decentralized) alternative. Evolutionary biologist Ernst Mayr (Mayr & Provine 1998) noted that biologists originally encountered "massive resistance" (preface, ix) to Darwin's theories for nearly a century after publication of *Origin of Species*, generally preferring more centralized alternatives. Mayr notes that it was not until the evolutionary synthesis between the years 1937–1947 that a general consensus was research on evolution (preface ix). Today, we can see the roots of the "intelligent design" perspective from Paley's very persuasive and intuitive argument (Cole 2007).

To be clear, it should come as little surprise that individuals have such strong cognitive dispositions to centralized approaches. A central designer in fact organizes many phenomena in the world. When people see neat rows of a crop in a field, they correctly assume that a farmer planted the crop and the neat rows allow for ease of harvesting. When people watch an American football game, they correctly assume that the movements of the players on the teams were planned by a coaching staff. When people notice the inner workings of a music box, they correctly assume that it was designed by an artisan. Furthermore, many of us participate in social systems where control and authority are very centralized.

Intuitions about systems in the world are influenced by our conceptions of ourselves. For instance, each of us experiences our own self as a singular entity. This is a very convenient, perhaps necessary, illusion for surviving in the world. When we do something, whether we are playing the guitar, exercising, or preparing notes for a lecture, we feel as if we are the "central agent". It feels like there is one entity in charge—namely, ourselves. As a result, we expect most systems to involve a central agent and someone must be in charge. The centralized mindset can therefore be viewed as a lasting remnant of the egocentrism that Piaget (as cited in Resnick and Wilensky 1998) identified in early childhood or what we found to be integral to our survival over long evolutionary time periods (Evans 2008).

Classroom data illuminate need for decentralized mindset emphasis

Previous work (Bishop and Anderson, 1990; Anderson et al. 2002; McVaugh et al. 2011; Lehrer and Schauble 2012), proposed four core areas of critical importance for understanding the concept of evolution—variation, selection, inheritance, and deep time—all of which present challenges to understanding evolution. The current work proposes adding a fifth component: a decentralized mindset (Smith 2010; Yates and Marek, 2013). Using empirical data to support our assertion that a decentralized mindset must be incorporated into the teaching and learning of evolution, our overall guiding research question is the following: How does the presence or absence of a decentralized mindset factor into an instructor's pedagogical ability to effectively teach evolution in secondary school?

Methods

Context

In order to examine how decentralized thinking (or lack thereof) manifested itself during a typical instructional unit on evolution, an exploratory qualitative approach was taken with four high school biology teachers (100%) from a science department in a large urban high school in the southwest United States that serves a predominantly Latino community. The participants in the present study were the four teachers who all taught biology to >95% of the study site's freshmen (ninth graders). The teacher participants are referred to by the pseudonyms Teachers A, B, C, and D. Personal participant data is found in Table 1.

While all the teachers' instructional units on evolution lasted approximately ten class meetings, the instructional activities implemented by each teacher were slightly different, and in the case of Teacher C, varied a great deal. The instructional approach carried out by Teachers A, B, and D was consistent in the fact that each teacher used that district-adopted textbook as an overall guide for lesson sequencing and ideas for instructional activities. Teacher C attempted to implement a more project-based approach to his instructional unit by having his students participate in short-term projects (e.g., creating word clouds on evolution and 30-sec. videos on the evolution of "anything"). For an outline of a typical lesson from each teacher on one day of his/her instructional unit, see Table 2.

Data sources

The present study used a variety of data sources from a larger data corpus. The main data sources included observations of four high school biology teachers (Teachers A, B, C, and D; 100% of biology teachers at the study site) in their classrooms during their evolutionary instructional units and pre- and post-observation interviews with these teachers regarding their personal perspectives on evolution, science teaching, student knowledge, and their classroom strategies for teaching evolution.

Since classroom observations were a major data source, the teachers' classes were observed and video recorded by the second author only when the teachers were present. A schedule was used to consistently observe an afternoon class from each teacher during his/her instructional unit. With the exception of Teacher C's observed Pre–Advanced Placement Biology class, all other observed classes were regular biology classes. All observations lasted the entire length of each class. All classes were approximately 45–50 minutes in length and scheduled to meet every day.

Along with being observed during classroom instruction, each teacher participated in individual pre- and post-observation, semi-structured interviews. Pre-observation interviews provided information about each teacher's background and classroom experience, evolutionary beliefs, and overall approaches to teaching science and evolution. In addition, the teachers were asked about the lessons they had chosen for their individual instructional units, how much time was usually allotted to the unit, the evolutionary concepts they routinely found their students having a difficult time understanding (applicable to the more experienced biology teachers), and the overall goals of the instructional unit (that is, the concepts and ideas they believed were important to get across to their students). Post-observation interviews were opportunities for each teacher to (a) relay insights and reflections about the issues and ideas that were raised by the students during the instructional unit, (b) explain the rationale behind certain activities that were chosen for the instructional unit, and (c) discuss adjustments he or she made to the lessons and the motives behind those adjustments. Each pre-observation interview took place approximately two to four class meetings before each teacher's instructional unit on evolution formally began. Each post-observation interview took place three to four class meetings after the conclusion of each teacher's instructional unit. All interviews lasted approximately 40–60 minutes, were audio-recorded and transcribed, and then member checked by the teacher participants for accuracy.

Lastly, in order to observe the potential impact of decentralized thinking had on the teachers' students, we measured the students' responses from specific questions that were most related to decentralized thinking on a modified version of the Conceptual Inventory of Natural Selection (CINS) (Anderson et al. 2002) as a pre- and post-test. Furthermore, the teachers were individually assessed with this instrument as well during a separate pre-observation interview. The CINS consists of three reading passages and 20 closed-response (multiple choice) questions with a series of distracters derived from well-documented alternative conceptions. Each reading passage describes a brief background of a particular population of organisms (e.g., the Galapagos finches) and establishes the context for the series

Table 1 Teacher participant personal data

TEACHER	YRS. OF BIOLOGY TEACHING EXPERIENCE	EDUCATION	NUMBER OF BIOLOGY CLASSES TEACHING	NUMBER OF BIOLOGY STUDENTS
TEACHER A	7	B.S. IN ZOOLOGY	6	94
TEACHER B	3	B.S. IN BIOLOGY AND LAND SURVEYING	5	81
TEACHER C	2	B.A. IN CHEMISTRY, B.S. IN BIOLOGY & BIOCHEMISTRY	5	82
TEACHER D	1 semester	B.S. IN BIOLOGY	6	82

Table 2 Outline of instructional activities from Day 6 of each teacher's instructional unit on evolution

TEACHER A	TEACHER B	TEACHER C	TEACHER D
DAY 6 LESSON TOPIC: Natural Selection & Evidence for Evolution	DAY 6 LESSON TOPIC: Natural Selection	DAY 6 LESSON TOPIC: Thoughts and Ideas on Evolution of "Anything"	DAY 6 LESSON TOPIC: Evidence for Evolution & Changes in Populations
Foldable activity on Natural Selection: Defining *fitness, adaptation, survival of the fittest, struggle for existence*	Written Warm-Up Questions: Evidence for Evolution, Natural Selection vs. Artificial Selection, Adaptations	Creation of 30-sec. evolutionary music videos (the evolution of any one thing)	Written Warm-Up Questions: Biological fitness, adaptations, overview of natural selection, evidence for evolution
Teacher relay of information: Evolution of Hawaiian Crickets	Natural Selection Candy Grab Simulation		Teacher-led lecture & presentation; guided notes: Evolution of populations, sources of variation
			Teacher-led demonstration: Using playing cards to represent gene shuffling

of questions that follow it. Ten concepts (*biotic potential, population stability, limited (natural) resources, limited survival, variation within a population, origin of variation, variation is inherited, differential survival, change in population,* and *origin of species*) related to natural selection are represented on the CINS (two questions per concept). In keeping with the objective of this article, we chose to focus on the students' responses to questions that addressed *origin of variation* because these questions specifically probed for understanding that "random mutations and sexual reproduction produce variations…" (Anderson et al., 2002, p. 965). The two specific questions asked the following:

(Question #6) How did the different beak types **first** appear in the Galapagos Islands?

a. The changes in the finches' beak size and shape happened because they needed to be able to eat different kinds of food to survive.
b. Changes in the finches' beaks happened by chance, and when there was a good match between beak shape and available food, those birds had more babies.
c. The changes in the finches' beaks happened because the environment caused changes in the finches' genes.
d. The finches' beaks changed a little bit in size and shape with each generation that followed, with some beaks getting larger and some getting smaller.

(Question #19) According to the theory of natural selection, where did the differences in body size in the three species of lizards most likely come from?

a. The lizards needed to change in order to survive, so helpful new features developed.
b. The lizards wanted to become different in size, so helpful new features slowly appeared in the new population.
c. Random genetic changes and sexual recombination of genes both created these differences.
d. The island environment caused genetic changes in the lizards.

Data analysis

Resnick's description of centralized thinking served as a fundamental guide with which to analyze the various data sources. According to Resnick (1996), in a centralized way of thinking, patterns in the world exist "only if someone or something creates and orchestrates" these patterns (p. 2). Resnick goes on to say that in a centralized mindset, "everything must have a single cause, an ultimate controlling factor. In general, decentralized approaches are ignored, undervalued, and overlooked" (1996, p. 2). Therefore, this description was used to code the data sources for occurrences of centralized thinking among the four teachers during their respective instructional units on evolution.

In order to answer the present study's guiding research question, the aforementioned description of a centralized mindset set forth by Resnick (1996) was used by the second author to code: 1) the teacher interviews and 2) teacher/student classroom interactions and teacher presentation of information involved in the potential emphasis of centralized thinking during each teacher's instructional unit on evolution. For an example of how such coding took place with one teacher's interaction, see Table 3. Conversely, Resnick describes the evolutionary concepts of variation and selection as being decentralized processes. Therefore, if a teacher exhibited a decentralized mindset by emphasizing variation and selection during his or her interviews or classroom practice, those particular instances were coded as such. Lastly, if any of the interview responses and classroom interactions did not demonstrate a decentralized or centralized mindset, then they received a code of "neither".

Results

Teachers' attitude and view of a particular topic can have an impact and influence their curricular and pedagogical decisions (Grossman 1990; Carlsen 1991; Hashweh 2005; Friedrichsen et al. 2011;). A biology teacher's view, then, of how evolutionary processes work can have potential importance in the various instructional strategies and activities that are chosen for lesson implementation. Data analysis of the teachers' classroom interactions indicated

Table 3 Example of classroom interaction coded as demonstrating a decentralized mindset (DCM)

Conversation	Codes
Teacher A: Is there much variation when you're doing asexual reproduction?	DCM
Student 1: No.	
Teacher A: No, 'cause they're just making copy after copy after copy. And so the only chance of genetic recombination would be a mutation. But when you have sexual reproduction, it increases the chances of genetic variation [Teacher A further explains using her deck of playing cards.] If these are Mom's genes, and these are Dad's genes [holding a half deck in each hand], and you shuffle them together to make babies, then each hand that you deal is the babies' set of genes that they end up with.	DCM

emphasis of decentralized thinking was largely absent from classroom instruction (see Table 4 for a summary of results from each teacher's classroom interactions).

In fact, when considering interview responses and certain key classroom interactions, Teacher C actually tended to exhibit more of a centralized mindset in his practice. The next section describes how the centralized mindset became apparent with Teacher C's practice.

Teacher C and the centralized mindset

From the beginning, Teacher C did not have any issue with teaching evolution and accepted the basic tenets of evolutionary theory. However, upon further questioning, Teacher C revealed ambivalence with his evolutionary acceptance. He enjoyed learning and reading about scientific and evolutionary concepts but admitted conflict with his personal spirituality (as if science and religion were in dichotomous opposition). Teacher C stated he had difficulty specifically with understanding the initial impetus that propelled evolution because of a lack of evidence from his perspective:

> But, to really understand, like, what's truly at stake of the whole … what drives all of evolution … I think that mostly everybody has no clue, you know, what's going on. … It's hard to see any evidence from the very beginning … from a point of origin … and then, that's pretty much where … you run into a lot of conflict with the whole religion idea in evolution. (Pre-observation interview, March 27, 2012)

Despite Teacher C's claims of not wanting to impart his personal values and thinking of evolution on his students, in several instances during his instructional unit his centralized mindset towards evolutionary theory became apparent. Teacher C's issue with evolution came from trying to understand the process at the molecular level, which partially explained why he would refer his students back to DNA-focused structure and processes. Specifically, Teacher C often questioned if there were some sort of outside molecular (i.e., centralized) force causing mutations to occur in DNA sequences, thus driving evolution forward. Since Teacher C, himself, questioned the process, he believed his students should question it as well:

> But, the one thing that when I … do that … just showing them how DNA does that … doesn't really show them how DNA gets its motive. And that's one thing a lot of people still don't even know. …We say it's energy-driven and there's a lot of other influences. So, I want them [the students] to actually kind of wrap their brain around that. … There is something smaller in there, and there is something that drives that smaller thing. I want them to kind of stop and think, "What is it that drives it and why?" (Pre-observation interview, March 27, 2012)

While Teacher C did not have specific assignments for his students that targeted this "motive" for evolution, he did have a specific video (which Teacher C knew spoke to intelligent design) that addressed the centralized force, and the issue was formally discussed at length on two separate occasions during the instructional unit. When this issue was discussed, Teacher C initiated all questions. Here is an example of one such instructional sequence:

> Teacher C: DNA has a lot of information, right? And it possesses a lot of information that can even pass on successful information to the next generation. But my question to you guys is look at it [has students look up at DNA models pasted to the ceiling]. Phosphate, a sugar, a nitrogen base pair. My question is how do they know

Table 4 Each teacher's percentage of interactions with emphasis of decentralized/centralized thinking among individual total teacher-student evolutionary interactions

	Number of total teacher-student evolution-related interactions during instructional unit	Teacher-student interactions with decentralized emphasis (%)	Teacher-student interactions with centralized emphasis (%)	Teacher-student interactions with neither emphasis (%)
Teacher A	181	8%	0%	92%
Teacher B	125	0%	0%	100%
Teacher C	88	0%	7%	93%
Teacher D	128	13%	0%	87%

> how to work together? How did they even come about? Figuring out, "Oh, yeah, Let's all come together." What drives them? That's the question: What drives them? What drives DNA? What drives it?
>
> Students: Their ancestors, to find better, to get better.
>
> Teacher C: They're made out of individual compounds. They're made out of elements, right? What have you guys been taught about elements? One single element is composed of what three things?
>
> Students: Protons, neutrons, electrons.
>
> Teacher C: What controls them?
>
> Student 3: The nucleus.
>
> Teacher C: What possesses those things to have? What do they possess?
>
> Student 1: There's a certain amount.
>
> Student 4: Energy?
>
> Teacher C: Energy. All this stuff is energy driven. Now how does it work? I don't know. (Observation, Day 5, April 3, 2012)

At first, Teacher C's students did not quite know how to respond to his line of questioning, perhaps indicating they, themselves, never thought of evolution occurring as the result of some sort of centralized "drive". It was not until Teacher C related the drive of DNA to the nucleus of an atom that the students seemed to understand the point Teacher C was trying to make. The teacher's questions, "How do they know how to work together?" and "What drives them?" are particularly emblematic of Teacher C's centralized mindset.

At the conclusion of his instructional unit, Teacher C still retained his centralized mindset. Whereas Teachers A, B, and D pondered ways to more effectively teach evolutionary concepts at the end of their respective units, Teacher C wanted more knowledge about the drive of evolution:

> Interviewer: Given the opportunity to sit down with a colleague that you trust—you can tell this colleague anything—maybe what you're weak in, what you'd like to be stronger in, what questions would you ask about evolution? Like, if they knew a lot about evolution, as far as content and as far as teaching it, is there anything that you would like to find out more, learn about more?
>
> Teacher C: Yeah. I think towards the end, the question I've always been wondering is what truly drives the smaller particles that are involved?
>
> Interviewer: You mean like the DNA.
>
> Teacher C: Even smaller than that … at the molecular level … and what drives that, and how does it store its information to be able to know what to do. That would be some of the questions I would have personally. (Post-observation interview, April 27, 2012)

Isolated instances of decentralized thought

Teachers A, B, and D accepted evolution as a fact and had no issues with teaching its concepts. All three teachers believed it was their responsibility as science teachers to "teach the science" and not necessarily dwell on the religious aspects to which evolutionary theory is linked. However, none of the three teachers gave a truly strong and consistent indication of a decentralized mindset as a fundamental idea for better understanding evolutionary concepts. The only instances where this type of mindset became somewhat apparent occurred during Teachers A and D's classroom instruction, when they both used a teacher-led card-sorting demonstration to facilitate explaining the origin of variation. One of these instances is illustrated in the following example from Teacher A:

> Teacher A: Is there much variation when you're doing asexual reproduction?
>
> Student 1: No.
>
> Teacher A: No, 'cause they're just making copy after copy after copy. And so the only chance of genetic recombination would be a mutation. But when you have sexual reproduction, it increases the chances of genetic variation. [Teacher A further explains using her deck of playing cards]. If these are Mom's genes, and these are Dad's genes [holding a half deck in each hand], and you shuffle them together to make babies, then each hand that you deal is the babies' set of genes that they end up with. [Teacher A deals cards on the table]. Alright, so each hand is gonna have a different set of genes. Each kid gets dealt a different hand. Are they coming from the same gene pool?
>
> Student 1: Yeah.
>
> Teacher A: Yeah. Mom and Dad, still, that's your gene pool. But, are the hands different?
>
> Student 2: Yes.

> Teacher A: Yes. Will they be different just about every time?
>
> Students: Yes.
>
> Teacher A: Yeah. So will that cause variation amongst the children of the family?
>
> Student 1: Yes.
>
> Teacher A: Yeah. Is it usually a huge variation, or is it smaller?
>
> Students: Smaller.
>
> Teacher A: Typically smaller things. You're not going to have a whole bunch of brown lizards and one red lizard from genetic shuffling. How could you end up with a red lizard in a brown lizard family?
>
> Students: A mutation.
>
> Teacher A: A mutation, something out of the normal shuffling. It wasn't part of your gene pool to begin with. It was something different. (Observation, Day 8, March 30, 2012)

The card-sorting demonstration utilized by Teachers A and D was an attempt to visually represent the ideas that gene pools with greater variation are the result of sexual reproduction and gene shuffling is a random process. Even though there is no centralized force involved in determining how genes from one generation are sorted and inherited by the next generation, the teachers did not set out to make this decentralized idea the focus of their lesson. Moreover, the emphasis of a decentralized mindset was not apparent, and based on observed classroom interactions, the students never appeared to comprehend or arrive at the conclusion that a decentralized mindset was essential to further understand evolution.

Absence of decentralized thinking

As evidenced by her classroom interactions and instructional activities, Teacher B devoted her instructional time to focused evolutionary concepts, such as *origin of species* and *evidence for evolution*. There was a single instance in which Teacher B clarified the origin of traits and it occurred during a lesson on *genetic drift.* In the following interaction, Teacher B's students were viewing a video that helps explain genetic drift. She paused the video to check for student understanding:

> Teacher B: Did you guys read that last part? What does that mean? "All the populations due to chance alone?" Do we get to choose our traits?
>
> Students: No. I wish we could!
>
> Teacher B: Wouldn't that be nice? If I could turn around and say, "Oooo. I really want that red hair!" Can I do that? No. I get what I get, right? Is that by chance? Are we doing this by chance? It's very random. Genetic drift is random because we don't choose what genes get passed over [on]. (Observation, Day 9, April 5, 2012)

Teacher B admitted she faced departmental pressure to conclude her instructional unit by a certain date because of the upcoming state-mandated student science assessment. As a result, Teacher B chose her lesson topics quite strategically and believed she sacrificed others. This reasoning certainly explains why the majority of Teacher B's classroom interactions were devoted to having her students understand speciation and how traits were passed from parent to offspring. Teacher B believed these emphasized topics were a priority to be taught in order for her students to better understand evolution.

Potential impact on student understanding

While some may acknowledge that decentralized thinking does not play an important role in further understanding evolutionary concepts, we argue that understanding the idea that mutations are stochastic in nature is essential to grasping how evolution works. We must emphasize that evolution, itself, is not a random process and that it is driven by environmental changes. Yet, we cannot ignore the fact that many students in the present study are struggling with the concept that novel traits in organisms initially arise through mutations, and not through some sort of centralized force. Table 5 summarizes this finding with the student results on two specific questions from the CINS.

As can be seen in Table 5, the present study's students demonstrated difficulty with this particular CINS concept. Students from Teachers A, B, and D exhibited slight gains from pre- to post-test with Question #6. Again, students from Teachers A, B, and D had gains with Question #19, with Teacher D's students demonstrating a more substantial gain (recall that Teacher D had slightly more interactions emphasizing decentralized thought at 13%). On the other hand, Teacher C's students did not exhibit any gains with either question, and actually demonstrated a negative effect with Question #19.

Discussion

Overall findings demonstrated that decentralized thinking was largely absent among these four teachers' practices

Table 5 Percentage of student correct responses on pre-/post-test specific CINS questions on "origin of variation" grouped according to each teacher

Pre-/post-test	CINS question on *origin of variation*	Teacher A	Teacher B	Teacher C	Teacher D	Average
Pre	Question #6	14% (n = 94)	11% (n = 81)	9% (n = 82)	11% (n = 82)	11.3%
Post	Question #6	15% (n = 104)	13% (n = 71)	9% (n = 74)	13% (n = 107)	12.5%
Pre	Question #19	44% (n = 88)	31% (n = 81)	40% (n = 78)	26% (n = 81)	35.3%
Post	Question #19	46% (n = 103)	34% (n = 59)	31% (n = 74)	37% (n = 107)	37%

during their instructional units on evolution. Even though this study took place within the context of one high school science department, there is no reason to suggest that a similar group of teachers in a school similar to the study site would demonstrate drastically different results. With this group of teachers, it is entirely plausible that they understood the stochastic nature of mutations (With the exception of Teacher A, all the teachers answered the specific CINS questions correctly), but that it simply did not occur to them to mention this nature explicitly to their students. While many may speculate about the teachers' own personal beliefs and content knowledge on the topic of evolution, it is also prudent to discuss the lack of emphasis of a decentralized mindset among various resources teachers utilize for planning and implementing lessons, such as the Next Generation Science Standards (NGSS) and state standards that are usually written with reform in mind and meant to provide a curricular coherence and direction for a specific content area.

The NGSS are designed to achieve coherence among the various science disciplines and across grade levels (National Research Council 2012). While it is not this paper's intention to provide a comprehensive critique of the standards, it is worth noting that while mention of a decentralized mindset is not specifically articulated, stochastic processes pertaining to inheritance in mutation and sexual reproduction do appear with some emphasis. For example, two of the Next Generation Science Standards (2013) evolutionary performance expectations for the high school level are listed below.

> Students who demonstrate understanding can . . . communicate scientific information that common ancestry and biological evolution are supported by multiple lines of empirical evidence. [Clarification Statement: Emphasis is on a conceptual understanding of the role each line of evidence has relating to common ancestry and biological evolution. Examples of evidence could include similarities in DNA sequences, anatomical structures, and order of appearance of structures in embryological development].
>
> Construct an explanation based on evidence that the process of evolution primarily results from four factors: (1) the potential for a species to increase in number, (2) the heritable genetic variation of individuals in a species due to mutation and sexual reproduction, (3) competition for limited resources, and (4) the proliferation of those organisms that are better able to survive and reproduce in the environment. [Clarification Statement: Emphasis is on using evidence to explain the influence each of the four factors has on number of organisms, behaviors, morphology, or physiology in terms of ability to compete for limited resources and subsequent survival of individuals and adaptation of species. Examples of evidence could include mathematical models such as simple distribution graphs and proportional reasoning]. (para. 1–2)

From reading these two student goals, a decentralized mindset is implied (through the use of understanding the empirical evidence that supports evolution) but not explicitly stated. A cursory overview of one state's 2012 high school biology standards for evolution also exemplifies this lack of emphasis:

The student knows evolutionary theory is a scientific explanation for the unity and diversity of life. The student is expected to analyze and evaluate:

(A) how evidence of common ancestry among groups is provided by the fossil record, biogeography, and homologies, including anatomical, molecular, and developmental;
(B) scientific explanations concerning any data of sudden appearance, stasis, and sequential nature of groups in the fossil record;
(C) how natural selection produces change in populations, not individuals;
(D) how the elements of natural selection, including inherited variation, the potential of a population to produce more offspring than can survive, and a finite supply of environmental resources, result in differential reproductive success;
(E) the relationship of natural selection to adaptation and to the development of diversity in and among species;
(F) the effects of other evolutionary mechanisms, including genetic drift, gene flow, mutation, and recombination; and
(G) scientific explanations concerning the complexity of the cell.

Essentially, decentralized thinking is not emphasized among curricular and reform-minded documents (e.g., state standards, NGSS) as a process-type skill. If anything, this mindset is emphasized only (at best) as a content-oriented concept. By placing more emphasis on the idea of decentralization, teachers would become increasingly cognizant of how evolutionary events are possibly (mis) interpreted by their students. Students, then, could engage in a deeper synthesis of how evolutionary processes occur. Nevertheless, a reading of another NGSS performance expectation does offer an entry point for emphasizing a decentralized mindset:

> Students who demonstrate understanding can . . . apply concepts of statistics and probability to support explanations that organisms with an advantageous heritable trait tend to increase in proportion to organisms lacking this trait. [Clarification Statement: Emphasis is on analyzing shifts in numerical distribution of traits and using these shifts as evidence to support explanations]. (Next Generation Science Standards 2013, para. 3)

This particular NGSS core idea aligns well with our proposed conceptual framework, in that incorporating mathematical statistics and probability when learning about variation in a population is a potentially powerful strategy for emphasizing a decentralized mindset, as students would be able to realize that a central control has little to do with how populations evolve. Moreover, a statistical understanding of variation and probability is seen as essential to having an accurate interpretation of how evolution occurs (Gould 1996). Bridging this decentralized gap may best be done through the application of statistics, probability, and mathematically based models, so that simulations like the card-sorting activities in which Teachers A and D engaged can be further conceptually supported and seem less abstract to students. Applications of other mathematically based models, such as using algorithms to explain various biological phenomena (e.g., diseases spread through a population), would also be powerful, as such algorithms demonstrate a decentralized mindset.

In earlier work we proposed four core areas of critical importance for understanding the concept of evolution: variation, selection, inheritance, and deep time. Each presents challenges to understanding evolution. With variation the major challenge is student understanding of statistics. Statistical understanding is essential for understanding of variation and probability (Gould 1996) and children as young as fourth grade have been able to develop statistical understandings (Petrosino et al. 2003; Lehrer and Schauble 2004). Improvements in understanding of evolution are observed when students practice with probabilistic reasoning (Alters 2005) and focus on within-species variation (Ferrari and Chi 1998). The second core idea is natural selection, which is based on three basic claims: a) All organisms tend to produce more offspring than can survive, (b) there is variation among organisms within a population, and (c) this variation is passed down to future generations through inheritance, has been frequently misunderstood by high school students (Demastes et al. 1995), undergraduates (Bishop and Anderson 1990), biology majors (Dagher and BouJaoude 1997), medical students (Brumby 1984), and science teachers (Nehm and Schonfeld 2007). Many of these misconceptions are Lamarckian in nature, suggesting that organisms determine what features they need and pass them down to their offspring. **A third concept**, inheritance or how traits are passed from one generation to the next, is challenging for students to apply this knowledge to evolution, instead holding that individual "needs" lead to changes throughout the species (Bishop and Anderson 1990; Demastes et al. 1995). The scaffolding and cognitive support needed to deal with inheritance must be provided during the early years of science education, and this can be accomplished through the use of instructional sequences or learning progression as explained by Catley et al. (2005). The fourth concept of deep time which is an understanding that the Earth is approximately 4.5 billion years old (Dodick and Orion 2003b). Dodick and Orion (2003a, b) developed the Geological Time Aptitude Test in order to identify the cognitive factors needed to understand and reconstruct geological systems and structures, such as fossil sequences. They identified three critical factors: (a) the transformation scheme, which describes the degree of change that occurs among a group of objects; (b) knowledge of geological processes, such as fossil formation; and (c) extracognitive factors, such as the understanding of spatial relationships (Dodick and Orion 2003a). Situating deep time within an evolutionary perspective, such as a tree-thinking framework, might go a long way in students' understanding of deep time. According to Catley and Novick (2009), instead of presenting evolutionary " events in disembodied time " (p. 330), secondary teachers should present these events in a relative manner, thereby giving students a "holistic trajectory" (p. 330) of such events. These four concepts are not distinct and unrelated to each other but overlap and interact in many ways making the instructional and cognitive challenges for understanding pronounced.

How can we bridge this lack of emphasis as a science education community? We believe there is promising leverage in mathematically based models. For example, mathematical algorithms explain various biological phenomena, like the way diseases can spread through a population or the movement of ants in a forest. Such algorithms offer opportunities to demonstrate and emphasize decentralized thinking. There is never a single, centralized, driving force as part of these algorithms. The understanding of self-organization and selection is essential for students to understand both complex systems (Jacobson, 2001).

Conclusions

In conclusion, we understand evolution as a combination of the processes of natural selection and genetic drift. Neither of these processes is centrally controlled. Furthermore, we propose there are five core elements of critical importance for understanding the concept of evolution: variation, selection, inheritance, deep time and decentralize thinking. Understanding these characteristics is critical to understanding evolution. Teachers and students that have developed an understanding of decentralized thinking will have a better understanding of evolution. In our study the students of teachers that had the highest percentage of teaching time using centralized concepts either did not improve on questions involving variation or their scores were lower between the pre-test and post-test. For a better understanding of evolution teachers need to be exposed to the ideas of decentralized thinking in their teaching of evolution.

Competing interests

The authors declare that they have no competing interests.

Authors' contributions

AP made substantial contributions to conception and design and interpretation of data. In addition, was involved in drafting the manuscript and revising it critically for important intellectual content, read and approved the final manuscript. ML made substantial contributions to the acquisition of data and analysis. MM provided literature review help as well as examples of decentralized work in biology and wrote and revised aspects of the manuscript. All authors have given final approval of the version to be published agree to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

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Author details

[1]Department of Curriculum and Instruction, The University of Texas at Austin, 1 University Station D5700, Austin, TX 78712, USA. [2]Department of Education, Santa Clara University, 500 El Camino Real, Santa Clara, CA 95053, USA.

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