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Research paper

Fostering creativity in science learning: The potential of open-ended student drawing

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HIGHLIGHTS

- Open-ended drawing can help make room for creativity in science.
- Nearly 40% of students creatively reinvented science examples in an imaginative manner.
- Students explored innovative alternatives to visual representation of concepts.

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ABSTRACT

This study examines the potential of open-ended student drawing serving as a springboard for creative performance and innovative ways of knowing in undergraduate biology. Our methodology takes into consideration visual stimuli (images on the instructor's PowerPoint slides), students' responses to an open-ended drawing task, and the sociocultural context in which these drawings were produced. Our visual design analysis revealed that nearly 40% of students ($n = 20/52$) opted for creatively reinventing science examples in a manner that was highly original and novel. It is argued that open-ended drawing can help open the doors of science instruction to student creativity and creative performance.

1. The creative nature of science

Creativity is an emerging topic in the field of science education, with a particularly prominent theme in this literature being that creativity is a central and defining aspect of the nature of science itself (McComas, 2008). Scientific inquiry is not an entirely objective and rational endeavor, as creativity plays an important role in the development of scientific knowledge. Scientific processes such as generation of hypotheses, design of procedures, interpretation of data, and derivation of conclusions all require a degree of imagination and creativity on the scientist's part. Rather than simply following a fixed, and failure-proof scientific method, scientists must creatively adapt and imaginatively make sense as they tackle procedural complications and unexpected results. Therefore, scientific knowledge production can be said to have important creative attributes.

Nevertheless, research shows that misconceptions about the nature of science are common (Lederman, Abd-El-Khalick, Bell, & Schwartz, 2002). When questioned whether scientists use their creativity and imagination during investigations, students and teachers typically provide responses such as “No, they [scientists] just have to give the facts, not imagine the stuff,” “[you] can't pretend things in science, so you can't imagine stuff,” and “logic plays a large role in the scientific process” (Akerson & Abd-El-Khalick, 2005). Whereas creativity is commonly viewed as an essential feature of artistic work, science is seen as a purely intellectual endeavor devoid of creativity and imagination. These students have yet to recognize that scientific knowledge production has a creative dimension. Such misconceptions about the nature of

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science are the result of exposure to curricular portrayals of the scientific endeavor as simply an objective pursuit of absolute truths, i.e. *facts* (Ford, 2006).

Compounding the problem, originality and creativity are rarely even discussed explicitly with students of science, except in the context of plagiarism and historical creativity (historical blurbs about famous scientists' work), as reported by Montuori (2010). The predominance of traditional *reproductive learning* (Robinson, 2001) approaches tends to limit students' opportunities to experience creative ways of thinking and being in science. This state of affairs begs the question of how to foster creativity in science learning.

2. Creativity and science

The meaning of creativity can vary considerably depending upon one's field of scholarship, disciplinary affiliation, and philosophical commitments. Thus, it will be convenient to give theoretical consideration to this elusive concept. Glăveanu (2010) makes a helpful distinction between historical and ordinary/mundane creativity. From a historical perspective, creativity is often seen as being the province of a few unique individuals endowed with unusual human capacity and intellectual ability (geniuses). From this perspective *historical creativity* refers strictly to the highest level of creation, namely game-changing novelties and paradigm-altering innovations that constitute landmarks in the history of a field (e.g., the work of eminent scientists like Einstein and Darwin; Fischer, Giaccardi, Eden, Sugimoto, & Ye, 2005). In the second perspective, focus shifts to the creative performance of the "normal person" (common creative acts, creative cognition, creative abilities, creative personalities, etc.), thus representing *ordinary creativity* (Bateson, 1999) and *mundane creativity* (Cohen & Ambrose, 1999), rather than dealing with the revolutionary breakthroughs of the "great creators". Ordinary or mundane creativity most often emerges in social contexts that are supportive and conducive to the performance of creative acts. This paper's primary focus is on ordinary creativity as manifested in a science lecture hall and creative drawings produced by undergraduate students in the context of a biology course.

We also theorize creativity as a high-order type of cognition. In commonly used knowledge hierarchies like Bloom's taxonomy (Bloom, Engelhart, Furst, Hill, & Krathwohl, 1956), creating is considered the highest cognitive level students can perform, surpassing other types of cognition such as remembering, understanding, applying, and analyzing (Anderson & Krathwohl, 2001). As the most cognitively demanding type of thinking, creating entails production of work that is original and novel (beyond the obvious). The creator cognitively operates "outside box" by synthesizing new ideas, doing something differently, designing/formulating something new, or transforming ideas/objects through imaginative manipulation/thinking. Likewise, in this study, we view creativity as a cognitively demanding ability that requires among other things, divergent thinking ability, fluency, and adaptability. Being creative requires deep thought.

Another important aspect of our theoretical perspective on creativity is the multiplicity of ways that one can be creative. Creative performance can be demonstrated in various modalities, including verbally (e.g., written, oral), figurally (drawing, photography) and spatially (movement, procedure). This is particularly evident in current theories and research, which typically attend to both visual and verbal components of creativity (Kleibeuker, De Dreu, & Crone, 2013; Price, Lovka, & Lovka, 2000) – subjects are prompted to write as well as draw to demonstrate their creative abilities. A theoretical model of scientific creativity is proposed by Simonton (2004), who posits that one can also be creative in discipline-specific ways and that creativity in science can be readily seen in scientists' production of patent, grant, and publication data. However, scientific creativity tends to decline over a science student's career, as their ideas become increasingly bounded by disciplinary knowledge and practices and chances of experiencing creative insights that may support paradigmatic change become smaller – a process akin to indoctrination (Simonton, 2004). Likewise, we view learners' scientific creativity developmentally, that is, as an emergent ability that can be developed in the science classroom as a result of learning experiences that are conducive to the performance of creative acts and the construction of novelty.

3. Creativity in science education

Formal science education has traditionally offered students little opportunity to practice and experience creativity. Rather than learned creatively, science is usually experienced as a reproductive or imitative endeavor whose engagement entails mainly student performance of uncreative acts such as copying, memorization, and regurgitation of facts. Evidence of such can be found in the prevalence of learning tasks such as trivia-like questioning that requires mere repetition of accepted bits of factual information (Oliveira, 2010), unoriginal demonstrations that simply replicate previously conducted experiments, verification labs that just confirm known results, and guided-inquiry activities in which students "rediscover" previously known answers to closed questions (Furtak, 2006). Such pedagogical activities afford little (if any) room for student performance of creative acts such as generation of novel questions/ideas or production of original science work. By and large, memorization and familiarity with the cannon takes priority over cultivation of student creativity or innovation.

Rather than nurturing learners' creativity, prevalent pedagogical practices in science can in fact suppress it. One such practice is exemplification (i.e., giving examples), which is commonly used by teachers to illustrate abstract concepts in science and clarify generalities that are difficult to grasp (Oliveira & Brown, 2016; Bills & Watson, 2008). Evidence exists that teacher-generated examples can inadvertently inhibit student creativity (Cropley, 2001; Galinsk et al., 2008; Watson & Mason, 2005). When asked to generate their own examples, students tend to simply repeat illustrations previously used by instructors. The authoritative status of teacher-generated examples renders them mentally salient – they are the first and often the only thing that comes to students' minds when prompted about a concept. As such, exemplification may serve as a source of creative constraints for learners due to mental bias and authority effects.

Likewise, Antink-Meyer and Lederman (2015) describe how US high-school students' divergent thinking ability, an important aspect of scientific creativity, declined after a 16-week academic semester. Instead of improving students' creativity, science classroom instruction led to lower scores on fluency (quantity of ideas), flexibility (variety of ideas), and originality (novelty of ideas). Students actually became less creative in asking questions, defining problems, planning and carrying out investigations, constructing explanations, and designing solutions over the course of their learning of the scientific material.

Creative learning is particularly uncommon at the higher education level where reading-style lecture remains the predominant method of teaching (Jackson, Oliver, Shaw, & Wisdom, 2006; Jones, 2007; Sutherland & Badger, 2004). University students learn primarily through practices such as lectures and recitations which prioritize lower-level cognitive abilities such as declarative recall (recollection of factual information) and conceptual understanding (comprehension of accepted ideas) rather than creative cognitive performance or innovative ways of knowing. Consequently, university students often drop out because they cannot come up with an original idea for a research project. As stated by Csikszentmihalyi (2006): “all their academic careers they have learned how to answer questions and solve problems set for them by others. Now that is their turn to come up with a question worth answering, all too many of them are at a loss” (p. Xviii).

4. Fostering creativity in science learning

Providing space for the development of creativity among students requires deployment of pedagogical tasks that have a relatively high degree of open-endedness as well as loose pedagogical structure. Rather than activities that are strictly regulated and focused on the cannon like drill-and-practice exercises, what is needed is learning tasks that are less constraining and more amenable to open/free exploration and meaning-making (van Oers & Duijkers, 2013). One such task is having students engage in imaginative question-posing for open-ended classroom investigations, such as having students invent investigatable questions from their own imaginations. As Chin and Osborne (2008) write, “the formulation of a good question is a creative act, and at the heart of what doing science is all about” (p. 1).

Among many other possibilities for fostering creativity in science learning are open classroom inquiries and open-ended problem-solving, as well as having students create (write or draw) their own examples of scientific concepts. As emphasized by Watson and Mason (2005), learners can be encouraged to become more creative through open-ended tasks involving example generation (“Produce the best example you can think of …“, “Find the least known example of …“, “Give a second/third example of …“). In these tasks, responsibility for being an active provider of examples shifts from the teacher to the student. As such, learner-generated exemplification opens new possibilities for students to be creative while writing and/or drawing scientific phenomena of their choice. This openness is consistent with current research emphasizing that creativity learning requires opportunities to engage in *divergent thinking* (Razumnikova, 2012) – reflective generation of multiple ideas – and *creative inquiry* (Montuori, 2012) — a more expansive and flexible type of exploration that is open to improvisation and novelty and aimed at pushing the dialogue to greater heights rather than a conversation-stopping truth.

Open-ended drawing has been shown to be particularly promising as a means to render science learning more creative. Drawing visual representations of natural phenomena (descriptive or explanatory diagrams of natural processes) is an effective way of fostering creative reasoning in science (Ainsworth, Prain, & Tytler, 2011). Inventing their own visualizations is particularly effective in the form of *open-ended representation challenges* (Tytler, Prain, Aranda, Ferguson, & Gorur, 2017) — learning tasks that combine investigation and drawing (collaboratively construction, negotiation, refinement and publicly sharing of visualizations). Drawing to reason in such open-inquiry contexts allows students to practice visual modes of representation prevalent in science such as the use of inscriptions for communicating scientific findings. This is the specific practice examined in this study.

It should be noted that our focus on drawing should not be taken as an interest in the integration of the Arts with Science, Technology, Engineering and Mathematics as advocated by the popular STEM-to-STEAM movement (Maeda, 2013; Radziwill, Benton, & Moellers, 2015). Despite its potential affordance of creative expression to science learners, it should be emphasized that drawing does not necessarily need to be approached as an artistic practice. Like artists, scientists also make extensive use of drawing (e.g., inscriptions). However, rather than setting out to produce artistic work, scientists resort to drawing for epistemological purposes such as creative data visualization. Moreover, scientists often find themselves drawing a doodle to visually depict something when discussing with colleagues, and it would be a difficult task to explain many scientific phenomena without using visual aid. As emphasized by scholars such as Ainsworth et al. (2011) and Binns, Smith, and Milligan (2011), science is inherently a visual field of study. Likewise, in the present paper, drawing is treated as a springboard for creative learning of science content, not an effort to integrate art into science; participating students did not receive any form of art instruction nor were they encouraged to position themselves as artists.

Regardless of specific pedagogical choice, the key is that students need to have access to a learning space that is cognitively less constraining and more divergent in nature (as opposed to convergent or closed) where they can play a more active ideational role. In this type of environment, students are more likely to embark on creative learning trajectory (van Oers & Duijkers, 2013) in which they can develop their creative thinking abilities and find their creative voices.

In an effort to address the above issue and find ways to make room for creativity, the present paper examines the potential of open-ended student drawings to serve as a springboard for creative performance and innovative ways of knowing in undergraduate biology. Our specific research question is: How effective is open-ended drawing as a pedagogical tool to foster creative student engagement in science?

Next, we describe our methodology approach to the study of creative science learning.

5. Methodology

An ethnographic research approach (Creswell & Creswell, 2018) was taken in this study. Data was collected through open-ended research methods such as classroom video-recording and an open-ended drawing task. Aligned with emergent and interpretive research traditions, such a flexible design is reflective of the challenges inherent to the empirical investigation of creativity. Researchers who set out in such an endeavor are faced not only with a lack of established methods and valid measures (Kahn et al., 2011) but also with the elusive nature of creativity (Montuori, 2012). Being creative depends, among other things, upon one's conception of creativity, disciplinary field (science, music, engineering, etc.), sociocultural background, cognitive and performative abilities, and personal attributes (motivation, passion; Jackson, 2006). Moreover, one can be creative in a multiplicity of ways, including linguistically, visually, mathematically, humorously, and so on.

Considering such complexities, we adopted a research design aligned with the research tradition of visual anthropology. Our methodological approach takes into consideration the visual stimuli with which students engage in class (e.g., PowerPoint slides, instructor dramatization of animal behaviors, etc.) as well as their creative responses to the visual stimuli (students' drawings and visual examples). As emphasized by van Leeuwen and Jewitt (2001), visual anthropology is an ethnographic method concerned mainly with the investigation of human engagement with visual representation through systematic examination of visual records of human experience.

5.1. Participants and setting

The participants of this study included a group of undergraduate students taking a third-year biology course on the topic of Animal Behavior. Enrollment consisted of a total of 52 students. The course was taught by the second author (henceforth referred to as Author 2) who held a Ph.D. degree in biology and had approximately 14 years of teaching experience at the university level. Additionally, Author 2 also had an artistic background and held a teaching philosophy that valued theatricality as a pedagogical tool. His creative teaching style, renowned at his department and university, was the main reason behind our selection of his classroom. He was known to effectively deploy what, from a scientific perspective, might be considered “unconventional practices” such as theatrical exemplification and creative drawing. As such, his biology class provided us with a unique opportunity to examine an educational setting where room is strategically made for creativity in science.

Aimed at introducing students majoring in biology to the scientific study of animal behavior, this 13-week course focused primarily on the ecological and evolutionary benefits of a variety of animal behaviors. The course met twice a week for approximately 1.5 h. During these meetings, Author 2 typically used PowerPoint slideshows and video-clips to engage students in the discussion of examples of animal behavior. When introducing new topics or behaviors, a video clip or image was presented to the class, giving a clear representation of the novel behavior or topic being introduced. The new behavior was then discussed openly with the class, allowing for active analysis of the example being presented. Experimental, comparative, or other additional examples were then shown and openly discussed to further analyze the relevant topic. Structured as concept formation lessons (Parker, 2011), students engaged deeply with sets of related examples as the instructor guided them. Examples were used to support student inductive construction of generalities central to the field of behavioral biology.

Throughout the lectures, questions between students and Author 2 often led to discussions about the behavior's adaptive value. Graphs of experimental data were also presented to provide empirical support for the behavior's function in nature. Author 2 ended each meeting by discussing the accepted theoretical framework and accompanying parameters involved in cost-benefit analysis with the class. Inductive analysis of a behavioral concept concluded with generalities accepted in behavioral biology.

Author 2 had been teaching this undergraduate course for several years. An animated and enthusiastic teaching style, accomplished with frequent hand gestures, changes in tone and inflection, and walking around the podium, was maintained over the course of the semester. PowerPoint slides were used to visually present examples through videos, photos, and diagrams. These visual elements were paired with anthropomorphic reenactment of the behavior under consideration. Author 2 frequently spoke from the animal's point of view, as if giving them conscious thoughts and a voice. Moreover, examples were often given in a parodic or comic style, with exaggerated movements and sounds that helped maintain a relaxed and informal atmosphere.

Author 2 viewed theatricality as a tool that he strategically capitalized upon to allow students in science classrooms to immerse themselves more deeply in the content of their learning material and gain a more meaningful understanding of it. He resorted to fantasy or parody to represent a conceptual message in a manner that was highly engaging and memorable to students. For him, it was only natural to theatrically model scientific concepts of a behavior's nature and make analogous comparisons between human and nonhuman action. Anthropomorphic analogies were meant to encourage students to conceive of unfamiliar nonhuman targets (animals' ways of behaving) in terms of more familiar human analogs (people's ways of being). He added, “the suspension of disbelief that is inherent of theatrical productions gives great freedom to switch between the narratives of different characters seamlessly and without jarring the audience with unnatural discourse. Once theatrical creativity has been established in an animal behavior classroom, it becomes natural to draw upon a large cast of animal actors to impersonate and to have them animate the lectures.”

It should be noted that the above information about Author 2's pedagogical practices is provided simply to illuminate the educational context in which students' creative learning of science is explored (not as an analytical account of his teaching performance). Our primary focus in the present study is specifically on the creative affordances of open-ended drawing. Analytical scrutiny of how students' creativity may have casually linked to Author 2's pedagogical practices is beyond the scope of this paper.

Consistent with emic approaches to ethnographic fieldwork (Bernard, 2002), inclusion of Author 2 as both a participant and as a researcher provided us with access to the perspective of an inside member of the visual culture under examination. As a scientist himself and someone familiar with the research site, educational context, and other participants, Author 2 was in a unique position to offer analytical insights into our emergent interpretations of the role visualization in science and the possible meanings attached to students’ drawings.

5.2. Data collection

The entire course was video-recorded and pictorial artifacts used for instruction (textbook illustrations, handouts, PowerPoint slides) collected for analysis. Then, at the end of the last course meeting, students were prompted to produce drawings by hand on a piece of paper using any materials available to them at the time (e.g., pen, pencil, markers, etc.). More specifically, students were given the following prompt:

> Using a drawing or illustration, please represent (to the best of your ability) a particular example of an animal behavior from this course that you found interesting or memorable for some reason and describe why you thought so (using words). You will not be judged on artistic merit.

Similar to previous studies of creative exemplification, we resorted to a drawing task that was open-ended both in terms of content and form. Like the *Droodles* (Price et al., 2000) long used by educational psychologists, our drawing probe was designed to assess our participants’ ability to process stimuli (science content learned during the class) in creative ways. Our work also shares some similarity with “draw-a-scientist” tests (Losh, Wilke, & Pop, 2008) in the sense that both methods rely heavily on visual data originating from the students themselves; students were prompted to perform visual acts. The images drawn by students served as communicative signifiers – symbols that “stood for” their individual understandings of a particular biological concept learned in the class. As externalized representations of a mental concept/cognitive state, these drawings visually communicated or depicted their thinking about a given animal behavior exemplified during the course. As elaborated below, this thinking was characterized as being creative to varied degrees.

When performing the drawing task, participating students had complete freedom to choose which particular concept to visually represent and how. Students were not explicitly directed to approach it in a more traditional (scientific) way or in a creative (artistic) way. Instead, our probe was designed to neutrally elicit examples from students without endorsing any form of visualization or imposing creativity *a priori*. Their creative acts were unprompted and spontaneous as traditional exemplification was not discouraged in any way. In the absence of objective measures of creativity (Antonietti & Colombo, 2012; Kahn et al., 2011), we used a task centered on ideational productivity and based on the assumption that creative thinking involves free production of ideas generated by a starting stimulus.

Moreover, our probe was designed to minimize any potential bias due to negative attitudes toward drawing. As research shows, many adults experience anxiety and self-consciousness when asked to draw (Dowd, 2018). Perception of drawing as a professional skill possessed only by talented artists rather than just a practice that anyone can use to observe the world commonly gives rise to a fear of being judged and a “I just can't draw” attitude. To prevent this, students were explicitly informed that their work would not be judged on artistic ability or merit.

5.3. Data analysis

To assess student creativity, we conducted a *visual design analysis* of the set of images in our collected data set (students’ drawings). Visual design analysis refers to the systematic examination of the semiotic ways in which pictorial representations represent and communicate meanings (Kress & van Leeuwen, 2006). Attention was given specifically to how students visually depicted their chosen example of animal behavior (i.e., the extent to which their representational choices could be considered creative or traditional). As previous research has shown, science itself has highly specialized forms of visual representation such as scientific inscriptions (Latour & Woolgar, 1986) and conceptual images (Kress & van Leeuwen, 2006). Characterized by a reduced degree of realism (e.g., solid backgrounds that lack details), traditional scientific imagery such as graphic displays provide abstract, generalized and decontextualized visual accounts of reality, being designed according to scientific convention, symbolism, and notation. Student drawings that did not abide to these scientific conventions of visualization constituted creative work.

More specifically, students' artifacts (paper drawings) were first digitalized and compiled into a single electronic document (a PDF file). As stressed by Collier (2001), making a systematic inventory or log of images is an important step in visual anthropology. The resulting dataset comprised a total of 52 student hand-drawings. Each drawing in our dataset was then comparatively examined against a catalog of images from the instructor's PowerPoint slides. Such comparative examination had the analytical goal of determining whether each drawing was a *reproduction* (a copy) of previously encountered image or an *original creation*. Student drawings in the reproduction category then underwent a second level of analysis, being further classified as *uncreative imitation* (a copy without any form of reinterpretation) or *creative reproduction* (a creative rendition). A number of examples of student drawings in each of these analytical categories can be found in the Supplementary Materials. This comparative classification resulted in an analytical scheme comprised of growing levels of creativity (see Fig. 1), which was used to assess the relative degree of creativity in students' visual work.

The above visual design analysis was supplemented with careful inspection of transcribed video recordings of pictorially rich instruction. Like iconographic approaches to visual semiotics (van Leeuwen & Jewitt, 2001), our study takes into account not only the images themselves but contextual data such as classroom interactions. Its scope goes beyond visually encoded meanings as we also explore the sociocultural context wherein student engagement in drawing production takes place. This expanded focus is reflective of our stance on student drawing as indicative of particular *visual cultures* (Sturken & Cartwright, 2009) in a given classroom setting. Drawings carry unique cultural meanings and can reveal (among other things) patterns of student socialization into preferred ways of seeing or looking favored by members of a particular social group. As such, it has the potential to illuminate pedagogical enculturation of novices into the visual culture of science.

An important premise of our analysis is that creativity is a choice. As scholars of creativity point out, human beings have *creative will* (Sternberg, 2006), that is, freedom to decide whether to invest our creative resources to the performance of a given task. Though creative performance can be constrained by unsupportive social contexts and influenced by cultural factors such as genres, current paradigms, and accepted styles, creativity is not simply determined by the external environmental factors. Instead, the creative person interacts with the context and choses to produce creative work (or not) based on considerations of factors such as effort, risk, reward, and punishment (Johnson-Laird, 1988).

Likewise, the highly supportive social context of our course where creativity was valued, endorsed, and practiced by the instructor himself, combined with the open-ended nature of the drawing task at hand served to give students room as well as encouragement to exercise their creative will. As our analysis soon revealed, many students indeed opted for creative performance of various forms (verbal, figural) and degrees (uncreative immitation, creative reproduction, and original creation). Emergent and grounded in the data itself, this analysis was informed by previous research that has shown that creativity entails, among other things, divergent thinking, innovate plays of ideas, and constraint

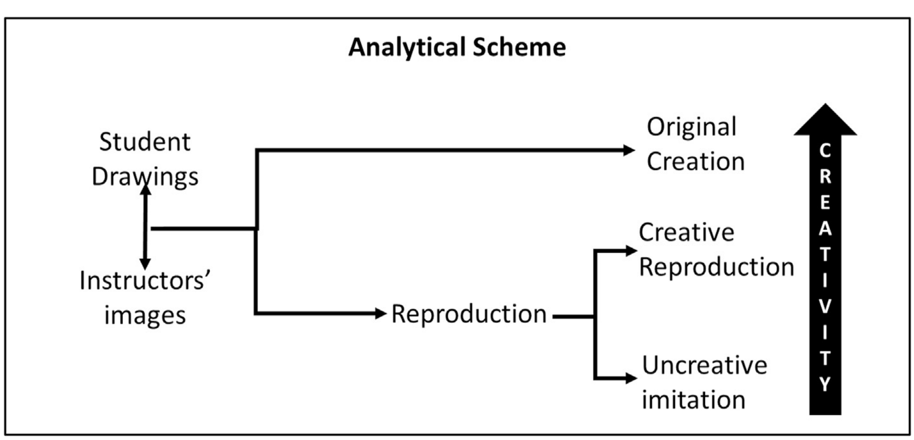

Fig. 1. Analytical scheme used to assess creativity in student drawing.

relaxation (Jackson et al., 2006; Okada & Ishibashi, 2017).

6. Findings

6.1. General trends

Several recurring features characterized the drawings of animal behavior produced by the students. Overlapping rather than mutually exclusive, these trends suggested varied levels of creativity. First, about 30% (16/52) of students' drawings were attempted reproductions of images encountered during the course completely devoid of creativity (uncreative imitation). With a high degree of similarity to photographs and/or graphs shown by the instructor during his PowerPoint presentations, these drawings suggested memorization and recall of visual input with minimal or little creativity. Other students (30% or 16/52), while reproducing familiar images, resorted to verbal creativity through the addition of a clever title, although the drawings themselves were not visually creative (creative reproduction). Lastly, the remaining students (40%, 20/52) favored figural creativity creating highly imaginative/visually original illustrations of animal behavior inspired by images seeing during the course. Relatively more creative, these anthropomorphic drawings often included speech and humor – examples were humorously reimagined and reinvented through an anthropomorphic lens. These trends are described in more detail below.

6.2. Uncreative imitation

Nearly one third of students' drawings (16/52) shared a high degree of similarity to the instructors' examples. These students performed at a low level of creativity by simply reproducing pictures of animals as well as display graphs to which they were exposed during the course. For instance, two students made drawings of an airborne gazelle 'stotting' and polyandrous guinea pig with very large testicles that were essentially copies of photographs from the instructor's PowerPoint slides. As can be seen on Fig. 2, these reproductive drawings shared a striking resemblance with the original images. Despite the apparent lack of creativity, students' ability to reproduce images of animals in so much detail (same visual focus, viewer orientation, and image composition) suggests a high degree of memorability.

Interestingly, uncreative reproduction was not limited to concrete and realistic imagery as many students also drew previously seen graphic displays (e.g., bar and line graphs) that were highly abstract in nature (Fig. 3). These graphic images depicted the empirical results of scientific studies discussed in class as metaphoric bars and lines in imaginary Cartesian space. Rather than providing a concrete portrayal of a particular animal (its physical appearance and how it behaved in nature), these graphic drawings depicted numeric data (containing statistical information) about specific animal behaviors such as the ungulate lekking polygyny (number of center vs outside mating opportunities) and a burying beetle's female forced monogamy (number of male beetles vs. the duration of males' pheromone emissions). These drawings indicate that the graphs shown by the instructor when giving examples also seemed to support visual encoding of quantitative information through increased imageability, hence facilitating student retention and recall of abstract empirical trends and quantitative evidence.

6.3. Creative reproduction

Though generally characterized by a high degree of imitation, student reproduction of PowerPoint images was not completely devoid of creativity. Performing at a slightly higher level of creativity, some students (16/52) generated reproductive drawings that were verbally creative by adding a witty title or speech balloon. This form of verbal creativity involves making creative use of language around an image or figure such as the addition of a clever title. Creative use of language results in shift or twist in how one would normally view the image (a humorous reinterpretation). This was particularly evident in the two student drawings in Fig. 4. Addition of the humorous title "STOT ME IF YOU CAN" and the speech balloon "what are you looking at?" this time gives rise to a verbally creative reproduction of the photographs of a stotting gazelle and the polyandrous guinea pig shown by instructor.

Likewise, some of the graphic displays reproduced by students were characterized by figural creativity, as evident in their generation of creative figures (as opposed to creative language). In this case, graphic displays of previously seen scientific evidence were redrawn from memory along with pictorial portrayals of the actual animals whose behaviors were the object of data visualization. For instance, when giving the example of Cuckoo birds' brood parasitism, the instructor showed a PowerPoint slide with a sonogram (soundwave patterns from the nest's occupants vocalizations; Fig. 5a).

As shown on Fig. 6, a student later reproduced the sonogram shown by the instructor and the image of a Cuckoo bird chick being fed by small surrogate parent. However, this student goes further and also generates a series of original figures of a Cuckoo bird chick pushing the host's egg out of the nest (not shown anywhere in the course) that visually captures/dramatizes what the instructor said orally ("*sometimes in the process even eject the eggs of the parent bird that were there in the first place*"). Devoid of any form of humorous or anthropomorphic verbalization, these creative graphic reproductions concretely dramatized an animal behavior while accurately depicting its scientific quantification as a reasonable hand-drawn facsimile of the hatchings in a sonogram of a bird chick's chirping.

Another example that was creatively reproduced by a student was the Giant Water Bug's parental behavior of back brooding. In this particular instance, the instructor showed a PowerPoint slide with a photograph of male Giant Water Bug carrying a large number of eggs on his back while discussing the possible advantages of such a behavior (oxygenation, protection against predators, etc.; Fig. 5b) compared to other possible behaviors such as simply laying eggs in the water or on emergent vegetation nearby.

A student later reproduced the image of the male Giant Water Bug with eggs on his back (Fig. 7c). However, this student goes beyond mere production and creates a drawing also characterized by a degree of figural creativity. In addition to reproducing the organism behind this parenting behavior, the student also visually depicts the process of oxygenation undergone by eggs laid in two distinct locations, namely in the water and on a leaf of a plant near the water (Fig. 6a and b, respectively). Ultimately, the photograph is creatively transformed into an analytic diagram that comparatively portrays the evolutionarily advantageous nature of this species' back brooding behavior.

6.4. Original creation

Nearly 40% of students' drawings (20/52) were characterized by interpretive anthropomorphism. Among these were some of the most creative student drawings found in our dataset. Many of these students performed at a high level of creativity by completely reinventing the examples of animal behavior given during the course in novel, original, and unexpected ways (i.e., visual reproduction was minimal or nonexistent). In these unique and unusual drawings, examples were completely reimagined and recreated through an anthropomorphic lens, being characterized by a high degree of creativity (both verbal and figural). For instance, one

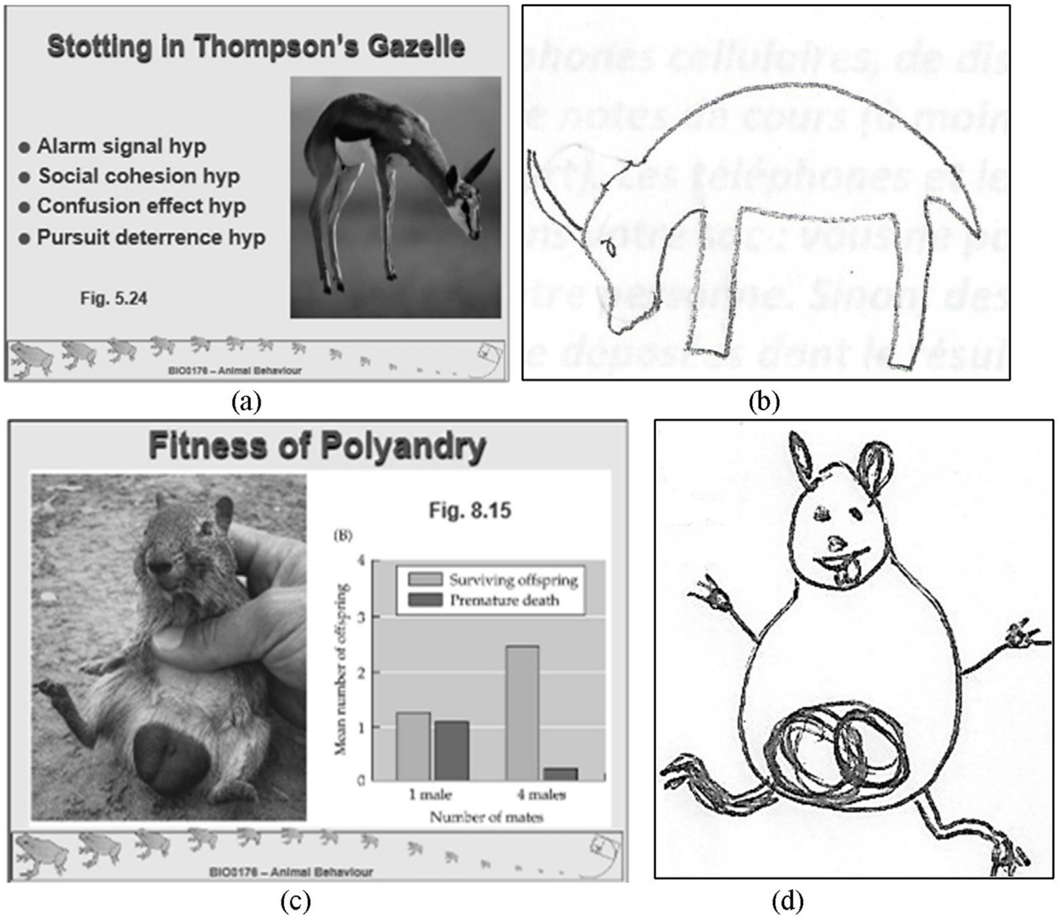

Fig. 2. PowerPoint slides with photographs of (a) gazelle stotting and (c) squirrel polyandry alongside students' reproductive drawings of these same images (b and d).

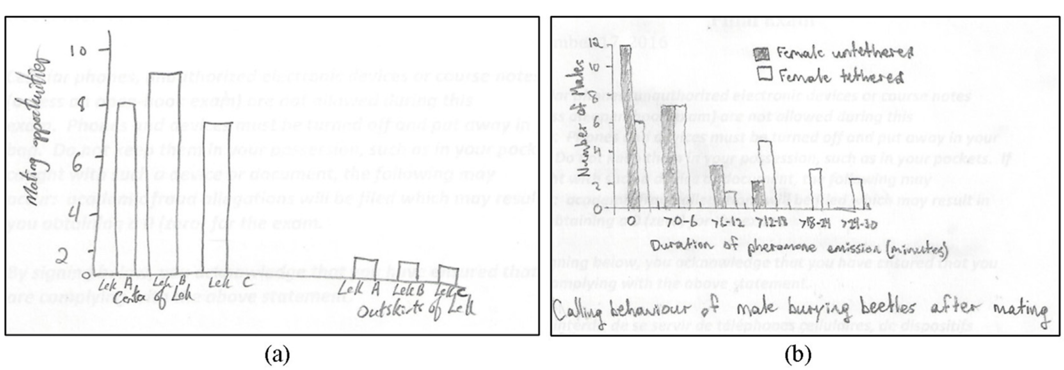

Fig. 3. Students' reproductive drawings of the empirical findings of scientific studies about (a) lekkings' polygyny, and (b) burying beetles' female forced monogamy.

student completely reinvented the Burying Beetle' female-enforced monogamy given by the instructor (Fig. 8a) as an anthropomorphic scene wherein a female beetle angrily utters "*How dare you cheat on me this way?! You are going to pay for this!*" as she throws a male beetle off a cliff, screaming "*I'm sorry!! Aaaaahhh*!!" as he falls down (Fig. 8b). Another student reinvented the instructor's example involving Cuckoo birds' mafia-like behavior (Fig. 8c) as an anthropomorphic scene at the top of tree where a sad looking bird stands by its nest as it is approached by a Mafioso bird who utters threateningly "*Take care of my eggs, or I will burn your house down!*".

In addition to the combined use of verbal and figural creativity, anthropomorphic drawings also differed from reproductive drawings in terms of visual style. Students who set out to reproduce imagery typically favored realism – they attempted to accurately capture the exact shape of animals as well as details of their body parts. This is particularly evident in the student drawing on Fig. 7, which resembles the type of scientific illustration often done by professional artists like botanical illustrators whose visual renditions of plant specimens that have artistic beauty as well as biological accuracy. In contrast, anthropomorphic drawings tended to resemble cartoonish illustrations in which animals were drawn with a more simplified/deformed body outlines and reduced realism. This is particularly evident in Fig. 8b whose characters can hardly be recognized as Burying Beetles. These students were

(a) (b)

Fig. 4. Students' creative reproductions of (a) gazelle stotting with humorous title "STOT ME IF YOU CAN"; and (b) squirrel polyandry with speech balloon "what are you looking at?.

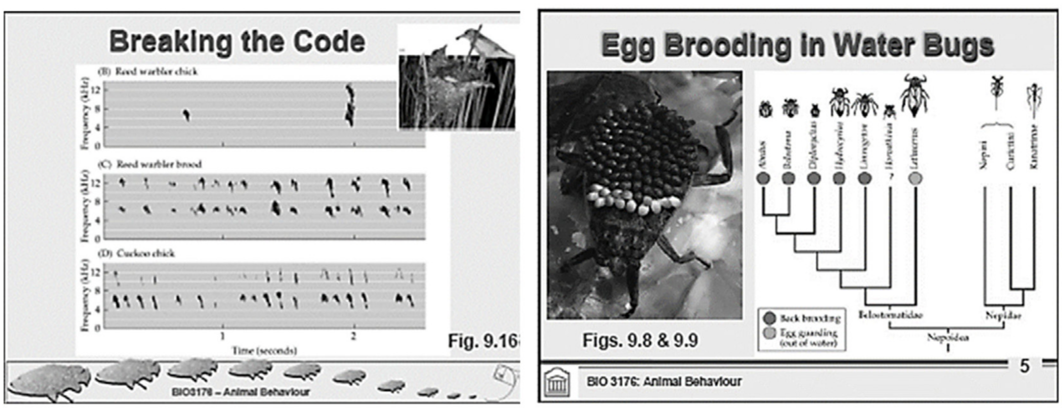

Fig. 5. PowerPoint slides shown by Author 2 with images of (a) bird sonogram and (b) a giant water bug's egg brooding behavior.

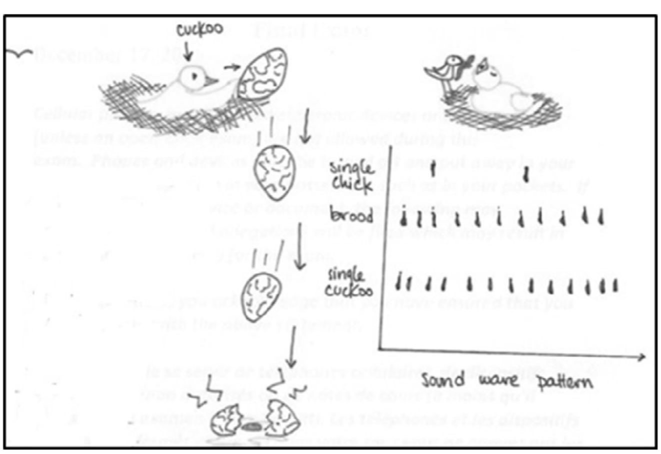

Fig. 6. Student's creative reproduction of the Cuckoo bird chick's sonogram depicted on instructor's PowerPoint.

clearly more concerned with telling a story visually than with realistically/scientifically depicting animals. Such a concern suggests that subjective interpretation (free and unconstrained) is being prioritized over objective reproduction. In other words, students who produced anthropomorphic drawings reserved the right to more freely interpret previously seen examples in a more personal and individualized manner.

7. Discussion

As indicated at the onset of this paper, opportunities for students to practice creativity in formal science education are scarce. Worse, prevalent pedagogical practices often suppress science learners' creativity, instead promoting imitative or reproductive learning. Evidence exists that students have a tendency to reproduce from memory images previously shown by their instructors (Smith, Ward, & Schumacher, 1993). As such, it seemed reasonable for us to expect low levels of creativity from a group of undergraduate biology students. However, contrary to our expectations, open-ended drawing revealed creative student performance of various forms (verbal, figural, etc.) and degrees (uncreative immitation, creative reproduction, and original creation). The significance of such finding is now considered.

7.1. Uncreative imitation and memorability

As described above, nearly one third of students' drawings favored uncreative imitation. Rather than taking the opportunity to be creative, these students opted for reproducing pictures of animals as well as display graphs to which they were exposed during the course. These reproductive drawings shared a striking resemblance with the original images. Despite the apparent lack of

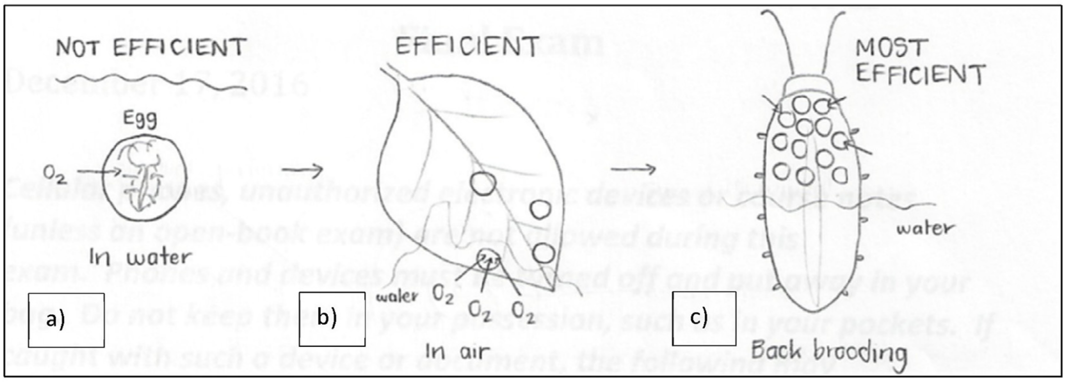

Fig. 7. Student's creative reproduction of the Giant Water Bug's back brooding from the instructor's PowerPoint slideshow.

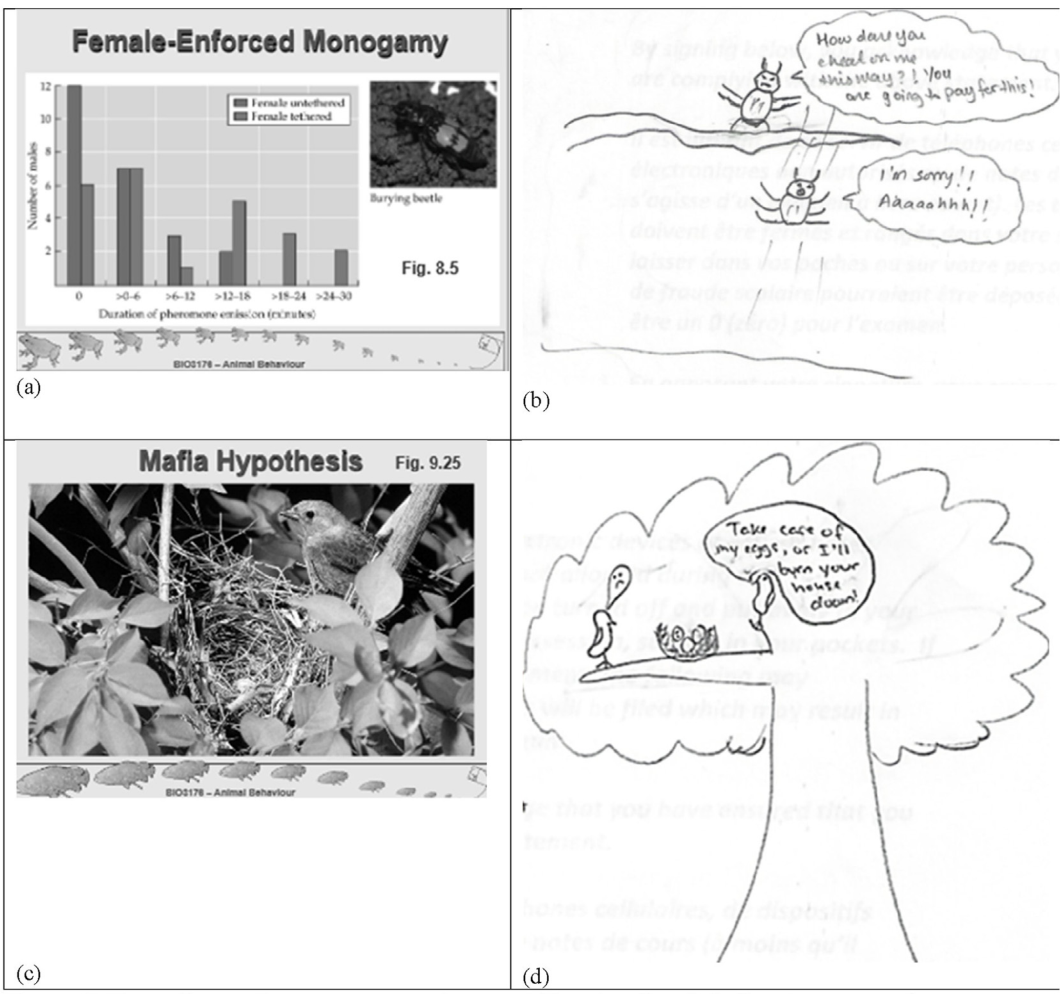

Fig. 8. PowerPoint slides with examples of (a) Burying Bettlee's female enforced monogamy and (c) Cuckoo bird's mafia-like behavior alongside students' anthropomorphic re-inventions of the same examples (b and d).

creativity, students' ability to reproduce images of animals in so much detail (same visual focus, viewer orientation, and image composition) suggests a high degree of memorability.

Such a finding is consistent with dual-coding theory (Sadoski & Paivio, 2013), which posits that concepts are stored in the learner's memory as a result of being encoded verbally (as words) as well as nonverbally (as mental images). Central to this cognitive process is imageability – how easy or difficult a concept is to imagine. Concepts that are highly imageable (i.e., can be easily associated with a mental picture) are more effectively stored and can be more easily recalled. As such, the highly realistic photographs shown by the instructor when giving examples seemed to increase the imageability of behavioral concepts such as stotting and polyandry. Even though these photographs did not always foster student creativity, they facilitated retention and recall of abstract information.

The above pattern of uncreative reproduction suggests that images encountered throughout the class may not have served as a source of inspiration for some students. It could be reasonably argued that these students' uncreative output was the result of their remaining uninspired by the visual stimuli generally available in the classroom. As previous research has shown (Okada & Ishibashi), creative inspiration often requires *deep encounters*, that is, prolonged, reflective, and careful observation of others' work that resonates with one's personal experiences, background, and interests (the work needs to "speak" to the viewer). However, the relatively large number of images included in the instructor's slideshow combined with the relatively fast pace of his presentation (due to time constraints) could have precluded students' encounters with illustrative images from reaching productive levels depth or relatability, thus preventing them from serving as sources of inspiration. A compounding issue is the fact that uncreative reproduction is less cognitively demanding. As such, reproducing a memorable image (as opposed to reinventing it in a novel and personalized way) could have provided uninspired students with a cognitively less demanding alternative to completing the drawing task. Additional research will be needed to illuminate the interplay of these multiple factors in giving rise to science learner inspiration.

7.2. Anthropomorphism as creativity

A strategy particularly common among those students how chose to be creative was anthropomorphic reinvention. As indicated above, nearly 40% of students opted for creatively reinventing science examples found to be interesting and memorable in an anthropomorphic manner that was highly original and novel. For these students, anthropomorphism served as a creative outlet that allowed them to interpret animal behavior more freely and to make creative leaps as they explored alternative ways of representing nonhuman action. Rather than positioning themselves as imitators who simply reproduced visuals in strict compliance with scientific norms of representation, these students seemed empowered to take on the role of creative inquirers who were willing to take risks and dared to explore innovative alternatives to visual representation of science concepts despite the possibility of being negatively judged from a more conservative science perspective.

Unusual and unique student work that deviates from teachers' imaginary norms (expectations for how students might possibly respond to an open-ended task) tend to be identified as error (rather than creativity) and dismissed as indication of poor conceptual understanding (Morgan, 1998). Likewise, in a biological context, anthropomorphism is commonly frowned upon as being scientifically inaccurate and an indication of misconception (Legare, Lane, & Evans, 2013; Orlander, 2016; Urquiza-Haas & Kotrschal, 2015).

Considering the above, it is worth pointing out that the examinations taken by the students during the course provided evidence that students' anthropomorphic drawings were not due to misconception or misunderstanding of science concepts. In one examination, Author 2 provided students the same image of the Burying Beetle's female-enforced monogamy (Fig. 8a) previously discussed in class and asked them to articulate a biological explanation for its contents. The same students who would later produce anthropomorphic depictions of this same behavior were able to describe it and explain its evolutionary roots in strictly non-anthropomorphic terms. Therefore, it stands to reason that students' anthropomorphic drawings were not rooted in mental representations with a *fallacious essence* (Kennedy, 1992), but were in fact manifestations of a creative disposition that was socially nurtured in the classroom.

The above finding is consistent with previous research showing that people can take different stances when trying to predict the behavior of different entities in the world, including a *physical stance* (centered on intuitive notions from physics) and an *intentional stance* (based on intuitive psychological notions about human behavior; Dennett, 1971). Likewise, students in the present study demonstrated an ability to take varied stances toward nonhuman behavior depending on the nature of the task they were asked to perform. Although an intentional stance was commonly adopted during the open-ended drawing task, formal course examinations invariably revealed an evolutionary stance toward animal behavior completely devoid of interpretive anthropomorphism. This multiplicity of stances suggests student attainment of divergent thinking, in particular cognitive flexibility during mental tasks involving interpretation of nonhuman action. As emphasized by scholars like Razumnikova (2012), divergent thinking is a major component of creativity and an important driver of creative thought. By allowing audiences of theatre to view and experience the story through the eyes of the actor, they become embedded within the imagination of the story, as well as remaining as objective observers from the outside. This approach also allows students in science classrooms to immerse themselves more deeply in the content of their learning material and gain a more meaningful understanding of it.

As Jackson (2006) adds, being creative also involves "working at and across boundaries of acceptability in specific contexts: it involves taking risks" (p.2). This is precisely what Author 2 accomplished through his adoption of creative practices such as anthropomorphic theatricality. By teaching undergraduate biology in such an unorthodox manner, Author 2 demonstrated to students how they could possibly be creative and at the same time encouraged them to work at the boundary of acceptability in professional biology. Rather than avoiding practices such as anthropomorphism and theatricality, he strategically used them as pedagogical resources to create conditions that effectively nurtured students' creativity. This more creative approach to undergraduate biology teaching was well received by students as evidenced by comments such as "the way the professor teaches this course is new to me in terms of the use of examples, but it is very interesting to know the processes from the animals' perspective rather than hearing only the theory behind it!"

Previous research on the cognitive processes underlying creative inspiration can shed some additional light on students' creative reproductions of biological examples. Research in this area emphasizes how imitation of others' creative work allows students to experience cognitive relaxation (Okada & Ishibashi, 2017). When copying others' visual work, students' cognitive constraints become more relaxed overtime, eventually enabling them to transition from simply reproducing to incorporating prior examples in creative and original ways. In other words, imitation constitutes an important source of inspiration for original and innovative creation. A similar process seemed apparent in the examined biology classroom. Inspired by the creative stimuli available in the classroom at the time of learning, students seemed generally inclined to go beyond reproductive performance and illustrate concepts of animal behavior in creative ways. As evidenced by the non-traditional nature of many of the drawings, students' cognitive constraints on the representation of animal behavior became more relaxed and thus more open to the manifestation of creative impulses (figural and verbal).

7.3. Humorous creativity

Another noticeable finding was the use of humor. As described above, a considerable portion of the students produced drawings wherein examples of animal behavior encountered during the course were humorously reimagined and reinvented in highly creative ways. Language and drawing were used not to copy or imitate but to creatively reinvent the exemplified nonhuman behaviors (e.g., a female beetle talking like a furious girlfriend, a Cuckoo bird talking like dangerous member of the Mafia, and a bird chick talking like the character of a famous movie). Students made "playful" use of science-related ideas.

Students' humorous drawings can be considered a form of innovative play. Their use of science-related ideas as a source of mirth and amusement suggests the rise of a playful drawing stance characterized by open-mindedness and receptivity to diverse ideas. As previous research has shown (Hansen, 2012; Kangas & Ruokamo, 2012), playful learning (a shared attitude of playfulness) creates opportunities for innovation and makes room for improvisation, both being essential to student development of creativity.

Though revealing, it should be noted that the present study is not without limitations. Among other things, it could be argued that having Author 2 as the practitioner and a researcher constitutes an important limitation as the researcher/practitioner may have inadvertently influence or bias in the study. For instance, as an educator committed to creativity, Author 2 was naturally inclined to perceive his own students as being creative. However, this tendency was kept in check during our recurrent peer debriefing sessions. Through systematic sharing and comparison our emergent interpretations, we were able to minimize any potential researcher bias to a reasonable level.

8. Conclusion

In sum, our research efforts revealed that open-ended drawing can help open the doors of science instruction to student creativity and creative performance. To a certain extent, its deployment in an undergraduate biology course gave rise to a learning space that was cognitively less constraining and more divergent in nature where students were likely to demonstrate their creative thinking abilities and chose to express their creative voices. However, the examined drawing task was not invariably approached creatively as many students refrained from engaging in unconventional ways of thinking and doing. This in turn raised questions about the possibility of science learners not finding inspiration in the existing curriculum, and the types of creative stimuli that may be needed to relax students' existing cognitive constraints and help them develop creative vision (the ability to imagine novel possibilities). Further research will be needed to better illuminate the inspirational roots of science creativity.

Another potentially fruitful avenue for future research is the integrated use of creative drawing for learning content throughout science instruction. Although creative drawing in this study was limited to the end of the examined course, its use can be extended and integrated throughout the curriculum. One possibility is the use of creative drawings as a form of personalized graphic organizer for content mastery. To this end, we have introduced what we call *creative cheat sheets* in more recent iterations of examined biology course. Like graphic organizers, these sheets are personalized visual aids in which students use visual symbols to creatively represent a large body of conceptual knowledge as they are exposed to new content (see Fig. 9). Creative representation is meant to facilitate memorization, recall and application of larger numbers of concepts. Students are allowed to bring a cheat sheet into the examination, but they are not allowed to use any words or numbers. As such, the students have to be creative and draw schematics and images in order to keep it very conceptual. Our initial observations point to an effective new means of promoting student content acquisition and achievement wherein creative drawing constitutes an integral part of the science learning process rather than just an "add-on" at the end. Moving forward, further researching this as well as other pedagogical uses of creative drawing will be essential for science educators recognize the full potential of creative drawing as a pedagogical tool that can be effectively used to promote content mastery and creativity in the

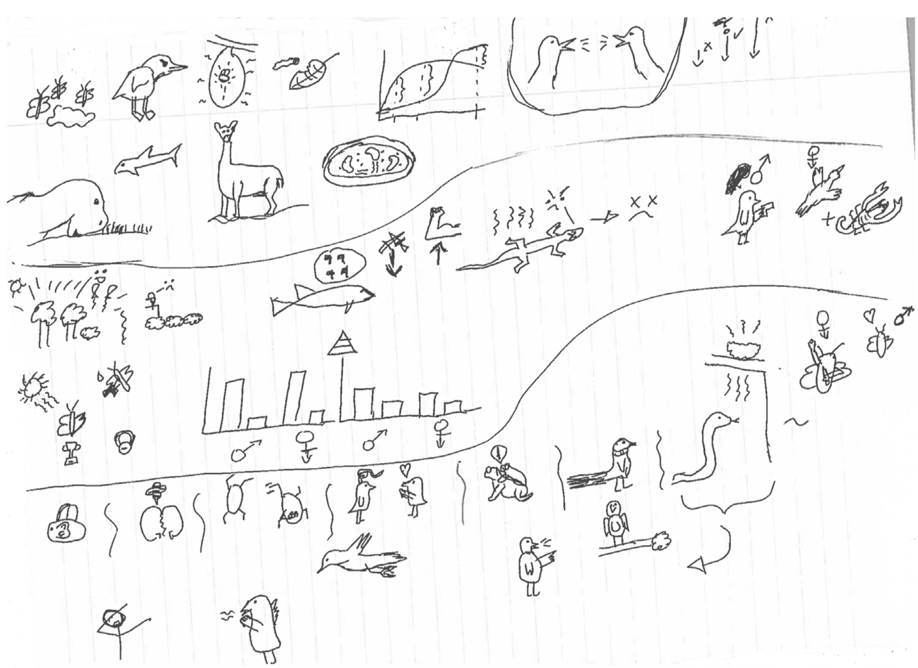

Fig. 9. Creative "cheat sheet" drawing by a student to represent the conceptual knowledge covered in the examined biology course.

science classroom.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.tate.2021.103416.

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