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RESEARCH REPORT

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Authorised cheat sheets in undergraduate biology: Using pictographic organisers to foster student creative cognition

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Abstract

Science student development of creative thinking ability is not sufficiently promoted and can even be inadvertently discouraged by current methods of instruction. Aimed at addressing this issue, the present study examined an undergraduate biology course in which scientific content instruction and creative drawing were integrated through use of *authorised cheat sheets* (personalised visual aids that students draw to bring for consultation during course examinations). Through a mixed-method analysis, we sought to identify the forms of student cognition that resulted, and how effective this pedagogical strategy was in promoting student creativity. Results indicate predominance of intermediary levels of student creative performance centred on the alteration of ideas and images encountered during the course (83% of drawings). In contrast, creation of original and novel images was considerably less frequent (only 6% of drawings). Authorised cheat sheets were found to be effective as a pedagogical tool for promoting student creativity in the form of structured imagination. Rather than limitless and unconstrained, the resulting student creativity was structured (constrained) by existing conceptual knowledge. Illuminating the relationship between pedagogical tools in a science classroom and students' emergent creativity, the present study underscores the critical need for educators to support student development as future creative professionals.

KEYWORDS
authorised cheat sheets, creative pedagogy, science creativity, student creativity, undergraduate science education

Context and implications

Rationale for this study

Although creativity plays a critical role in scientists' work, student creative thinking is not promoted in many science classrooms and can even be inadvertently discouraged by current methods of instruction. There is currently a need for a more advanced, theory-based understanding of how science instructors can foster student development of domain-specific creativity.

Why the new findings matter

Integration of scientific content instruction with creative drawing is shown to give rise to a wide spectrum of student cognition (diversity of thought). This integrated approach gives students the opportunity to go beyond mere replication of concepts and practise structured imagination (i.e., engage in creative performance based on conceptual knowledge).

Implications for instructors and educational researchers

At a practical level, this study describes a pedagogical strategy, namely cheat sheets, that instructors interested in promoting student creativity while learning scientific content can use in their own classrooms. Practical guidance is provided on its classroom implementation. At a theoretical level, this study provides researchers with a more sophisticated way of conceptualising student creativity and inspiration in science in terms of psychological constructs such as cognitive fluidity, cognitive relaxation, cognitive tinkering, cognitive diversity, and so on. These constructs can be used in future research to systematically examine students' trajectories of creativity development and hence advance our understanding of science creativity.

INTRODUCTION

> I am enough of an artist to draw freely upon my imagination. Imagination is more important than knowledge. Knowledge is limited. Imagination encircles the world.
>
> Albert Einstein, 1929

Einstein's perception of himself as both an artist and as a scientist and the importance he places on drawing upon his own imagination lend support to the widely accepted position that creativity plays a critical role in scientists' work and in the development of scientific knowledge (Oliveira et al., 2021; McComas, 2008; Sternberg, 2010). Deemed the 'human capital of a country' (Lin, 2014, p. 45), creativity has been increasingly recognised as a critical concern of educational efforts aimed at preparing students for their future professional lives. As we edge closer to marking 25 years since the publication of the foundational document, 'All Our Futures: Creativity, Culture, and Education' (NACCCE, 1999), commonly referred to as 'The Robinson Report', creativity continues to gain traction as an essential skill for twenty-first century success (Durham University, 2019; International Society for Technology in Education, 2022; Partnership for 21st Century Learning, 2017). As such, science education 'has key roles in the creative and cultural development of young people' (NACCCE, 1999, p. 77).

Today, 'novelty' (or originality) and 'value' (or purpose) are widely accepted as essential characteristics when defining creativity, to which the NACCCE (1999) also adds 'imaginative activity' (p. 30). Policy makers worldwide have come to recognise that 'nurturing students' imaginative and creative thinking is an investment in their country's future' (Beghetto, 2008, p. 134). No longer limited to the arts or viewed as a luxury within the curriculum (Craft, 2008; Patston et al., 2021), creativity has emerged as an essential skill for twenty-first century success (International Society for Technology in Education, 2022; Partnership for 21st Century Learning, 2017) as leaders seek to claim a place in the global economy and invest in the creativity of their people, what Lin (2014) calls 'the human capital of a country' (p. 45).

Despite consensus that creativity is a key factor in future individual and collective prosperity, educational research shows that such recognition is yet to be translated into practice. Evidence exists that formal education can actually serve as a deterrent to student development of creativity. Opportunities for creativity development are particularly limited among young people from disadvantaged backgrounds who are at risk of being culturally marginalised (Durham University, 2019). Antink-Meyer and Lederman (2015) describe how high school students became less creative in asking questions, defining problems, planning and carrying out investigations, constructing explanations, and designing solutions after a 16-week science course. According to Kim (2011), while US student scores on the Scholastic Assessment Test (college entrance exam in the USA) have increased since the 1990s, scores on the Torrance Test of Creative Thinking (TTCT) have significantly decreased. When asked to self-assess their creative abilities, students usually report a decrease in their ability to be creative as they progress through school (Armstrong, 2016; Beghetto et al., 2011). Similarly, Csikszentmihalyi (2006) describes the plight of university students who chose to drop out because they were unable to produce an original idea for a research project.

Combined, the above studies paint a troubling picture of formal education. Across the 5–16 educational spectrum, student development of creativity remains largely unsupported and can even be inadvertently discouraged by current methods of instruction. This problematic trend comes at a time when education has become more test-driven (Starko, 2018). Such tests, which typically rely on knowledge retrieval rather than critical thinking, 'can result in teaching practices that focus on little more than the memorization of fragmented facts… imaginative thinking can be driven out of the curriculum, because it is viewed as irrelevant or even potentially disruptive' (Beghetto, 2008, p. 135). The result is a state of affairs that has been described in the United States as a 'creativity crisis' (Brownson & Merryman, 2010).

In an effort to tackle this crisis and achieve a more advanced, theory-based understanding of creative thinking in science education, the present study examines an undergraduate biology course in which scientific content and creative drawing were systematically integrated. Such integration was accomplished through the pedagogical use of *authorised cheat sheets* (Dickson & Miller, 2005; Erbe, 2007; Song & Thuente, 2015), defined as personalised visual aids that students draw to bring for consultation during course examinations. These sheets take the form of pictographic organisers wherein conceptual forms of visual representations (symbols, schematics, etc.) are creatively used by students to represent science concepts encountered as they are exposed to new content. As such, we set out to build on previous work pointing to the potential of open-ended drawing (Oliveira et al., 2021) to serve as a pedagogical tool that can be effectively used to enable university-level students to experience science creatively and to promote creative learning of scientific content. Within this context, our study sets out to answer the following research questions:

1. What forms of student cognition emerge (creative, imitative, divergent etc.) as a result of the introduction of cheat sheets into the biology course?
2. How effective were cheat sheets in promoting student creativity in undergraduate science?

STUDENT CREATIVITY AS CREATIVE COGNITION

In this study, we take a developmental, cognitive stance on student creativity. For us, student creativity is fundamentally a high-order level of cognition. Informed by commonly used knowledge hierarchies like Bloom's taxonomy (Krathwohl, 2002), we view creative production as the highest cognitive level students can use to demonstrate their learning, surpassing lower-level skills such as remembering, understanding, applying and analysing (Anderson & Krathwohl, 2001). At this level, the creator operates 'outside the box' by synthesising new ideas, doing something differently, designing/formulating something new, transforming ideas/objects through imaginative manipulation/thinking. This cognitive demand requires, among other things, divergent thinking ability, fluency and adaptability. Being creative requires deep thought.

Informed by previous scholarship (Guilford, 1950; Kupers et al., 2018; Lin, 2011), we view creativity as a cognitive ability that students can develop over time and that can be pedagogically fostered within the context of a science classroom. Rather than an innate quality possessed by a lucky few who are born with an exceptional talent, we view creativity as a skill that all students can develop by practising the construction of novelty in social contexts that are supportive and conducive to the performance of creative thinking. Science instructors can help students make strides in reaching their creative cognitive potential by teaching creatively and teaching for creativity, practices described as developing materials and instructional approaches that inspire student interest and motivation (Jeffrey & Craft, 2004; NACCCE, 1999). Within the classroom, teachers can support students as they engage in everyday creativity, or 'mini-c' creativity, which 'not only broadens the developmental continuum of creativity (from mini-c to little-c to Big-C) but also highlights the creative, transformative process involved in developing personal knowledge and insights' (Beghetto & Kaufman, 2007, p. 74).

Creative thinking can be demonstrated in various communicative modalities, including verbally (e.g., written, oral), pictorially (drawing, photography) and spatially (movement, procedure). This is particularly evident in previous studies in which subjects were prompted to write as well as draw to demonstrate both verbal and visual creativities (Kleibeuker et al., 2013; Price et al., 2000). Starko (2018) argues that 'real-world creativity takes place in a domain' (p. 17). Being creative in science, according to Barrow (2010), means that students have mastered the disciplines' conceptual ideas and are able to work through a process of synthesising previously unrelated knowledge into a new relationship. Antink-Meyer and Lederman (2015) linked science creativity to the fluency (quantity of ideas), flexibility (variety of ideas), and originality (novelty of ideas) of student work. Simonton (2004) conceived of scientists' creativity in terms of their production of novel professional work (patents, grants and data).

In a science classroom, such knowledge would be presented through the application or inference of information, observation of important details, interpretation of data, generation of predictions and hypotheses, communication of scientific findings and the formulation of conclusions. Refining these skills at an undergraduate and graduate education level sets a foundation for future scientists to foster the required theoretical and analytical competency needed to succeed in the field, rationalised by the belief that the development of creativity is just as essential as critical thinking in a science classroom (Rodríguez et al., 2019). The present study focuses on the pictorial representation of domain-specific creativity as manifested in conceptual drawings produced by undergraduate biology students.

Going beyond simplistic dualities (e.g., creative vs. uncreative), we conceive of student creative cognition as being performed by students at various levels characterised by increasing degrees of complexity. Aligned with Fischer's skill theory (Fischer, 1980; Fischer & Bidell, 2006; Fischer & Farrar, 1987) and Commons' model of hierarchical complexity (Commons, 2014; Commons, Gane-McCalla, et al., 2014; Commons & Goodheart, 2008; Commons, Li, et al., 2014; Commons & Richards, 2002), we consider creativity to be a skill (capacity to act) that students develop through levels of increasing complexity within a dynamic system that includes interactions between the self and other(s) in a supportive social environment. As students become more creative, they dynamically progress along a hierarchical sequence being influenced by contextual and interpersonal factors. This theoretical perspective is also informed by existing research. In a previous study (Oliveira et al., 2021), we found that students' biological drawings demonstrated three distinct performance levels of increasing creativity: (1) *uncreative imitation*—exact copies of images previously encountered during science instruction (e.g., photos from the instructors' PowerPoint slideshow); (2) *creative reproduction*—modified copies of previously encountered images wherein new visual or verbal elements are incorporated; and (3) *original creation*—a completely novel visual rendition of a science concept learned in class. Nilsson (2011) proposed a similar but more nuanced taxonomy of student creative performance composed of five levels. From least creative to most, it is as follows: *imitation* (nothing novel in content or form), *variation* (modification to an existing work), *combination* (mashing two existing works together), *transformation* (changing the material or medium of an existing work), *original creation* (influence of other works is unrecognisable, novel in both content and form).

A careful comparison will reveal similarities as well as differences in how Oliveira et al. (2021) and Nilsson (2011) distinguish between the various levels of student creative performance. On both scales *original creation* of an image or idea is the highest classification of creativity. The lowest levels of creativity also coincide in terms of their focus on *imitation* (exact reproduction of an image or idea). The difference between the two studies lies in the middle where Oliveira et al.'s (2021) notion of *creative reproduction* (modification of a familiar image) is split into three distinct levels that Nilsson (2011) calls *transformation*, *combination* and *variation*. As such, Nilsson (2011) emphasises that there are multiple ways that one can modify an existing idea (i.e., modification of existing ideas can be visually performed with various degrees of creativity). One can change the medium of the idea (i.e., transform it), one can change the idea by meshing it together with another idea (i.e., combining them), or one can simply embellish the idea (i.e., vary it). Informed by these previous studies, we conceive of student creativity as a type of cognition that can be situated along a performance continuum depending upon the students' level of original thinking (Figure 1). Students' level of creative performance is demonstrated in the pictographic choices (specific ways of visually representing certain science concepts) they make while visually represent-

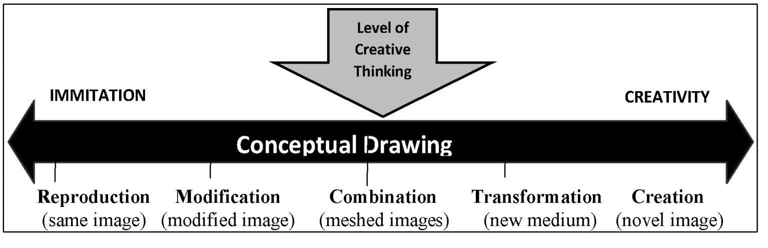


FIGURE 1 Performance continuum with five levels of student creative thinking.

ing science concepts. Spanning the spectrum from an Imitation end (exact reproduction) to a Creativity end (novel creation), this continuum is composed of five performance levels that reflect the amount of creative thinking demonstrated by students in their cheat sheets. Such analytical distinctions allowed us to distinguish among the varied types of creative cognition demonstrated by students when drawing science concepts (Question 1) as well as assess the effectiveness of cheat sheets in encouraging students to become more creative (Question 2).

LITERATURE REVIEW

From imitation to creativity

Some approaches to instruction have reduced the sciences to facts, rules and terms to be memorised, failing to translate the 'processes and understandings that are integral parts of real-world science' (Starko, 2018, p. 246). Not only is creativity itself a topic rarely discussed in science classrooms (Montuori, 2010), but science is also a discipline that students predominantly experience as a reproductive or imitative endeavour. Evidence of such can be found in the prevalence of 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 hands-on activities in which students 'rediscover' previously known answers to closed questions (Furtak, 2006). This predominance of *reproductive learning* pedagogy (Robinson, 2001) may place limitations on students' opportunities to experience creative ways of thinking and being in science. Instead of generating novel questions or ideas or producing work with any degree of originality, students gain practice in imitation.

This problematic state of affairs has been shown to give rise to misconceptions about the nature of science (Lederman et al., 2002). Students begin viewing science as a purely intellectual endeavour, devoid of creativity and imagination (Akerson & Abd-El-Khalick, 2005), which is inconsistent with the demands of the field. As emphasised by scholars like Hadzigeorgiou et al. (2012), scientific ideas are 'creations of the mind' (p. 603). Scientific processes such as generation of hypotheses, design of procedures, interpretation of data and derivation of conclusions all require a certain degree of creativity. As emphasised by researchers such as De Cruz and De Smedt (2010) and Ward et al. (2002), scientific creativity is central to the advancement of the field. Just as in the arts, science calls for creative abilities such as originality, flexibility and appropriateness to pursue innovative projects and goals (Amabile, 1996). Creativity is essential for the occurrence of conceptual shifts in thinking, being rarely produced by a standardised set of generic rules (Boden, 2004). Creativity plays an important role not only in the generation of new ideas, but also when it is necessary to pivot to new potential applications (Oliveira et al., 2021). Without creativity, scientific knowledge production would inevitably become stagnant and devoid of innovation.

Presently, the typical science classroom tends to enable the opposite effect in students, instead opting for standardised testing practices and encouraging lower-level cognitive functions such as memorising. Studies such as Noddings (2013), suggest that the current standards and curriculum may contribute to a loss of creativity in students. Yet, a science classroom plays a key role in the development of future innovators and scientists, and hence should be characterised by pedagogical approaches that support the creativity of their students (Antink-Meyer & Lederman, 2015). This includes encouraging, supporting and challenging students with the course material while creating a safe learning environment (Teo & Waugh, 2010).

Shifting toward creativity

Science education becomes inauthentic when teachers merely tell students what is true (Starko, 2018). Tynjälä (2001) frames this issue as a matter of subject-matter mastery: experts are capable of generating and transforming knowledge, while students are primarily asked to acquire, reproduce and demonstrate their knowledge. If creativity is a necessary skill, as previously discussed, there is an argument to be made to pivot towards modernising teaching practices to better facilitate deeper comprehension of the material (Oliveira et al., 2021; McCune & Entwistle, 2011).

Science teaching, according to the cognitive approach, 'may be adapted to develop creative reasoning patterns' (Kind & Kind, 2007, p. 18). Shifting the instructional dial from the imitative to the creative end of the cognitive spectrum requires deployment of pedagogical approaches with a higher degree of open-endedness and structural flexibility. This need for presenting students with open-ended tasks is consistent with current research emphasising that creative learning requires opportunities to engage in *divergent thinking* (Razumnikova, 2012; Van Oers & Duijkers, 2013)—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. To develop as creative thinkers, students need access to a learning space that offers more cognitive freedom and is more open to intellectual exploration where they can play a more active ideational role (Beghetto & Kaufman, 2014; Kupers et al., 2018).

Different approaches to support creative teaching and learning in the science classroom have been examined by educational researchers. One approach is having students engage in imaginative question-posing for open-ended classroom investigations. 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). As emphasised 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…').

Another possibility is having students write or draw their own illustrations of scientific concepts. Open-ended drawing has shown promise in promoting student creativity in science. Drawing visual representations of natural phenomena (descriptive or explanatory diagrams of natural processes) is a productive way of fostering creative reasoning in science (Ainsworth et al., 2011). Inventing their own visualisations is particularly effective in the form of *open-ended representation challenges* (Tytler et al., 2017)—learning tasks that combine investigation and drawing (collaboratively construction, negotiation, refinement and publicly sharing of visualisations). Often used as a diagnostic tool, such drawings provide insight into the students' depth of understanding, affording students the opportunity to represent material in a manner that most makes sense with their own conceptualisations and semantic features (Nalaka & Samarakoon, 2021; Nyachwaya et al., 2011). This allows instructors the opportunity to correct misconceptions while improving critical and divergent thinking abilities (Nalaka & Samarakoon, 2021).

Cheat sheets

In higher education, one specific example of creative pedagogy that has received attention is student construction of authorised cheat sheets to be used for course examinations. Exams with authorised cheat sheets differ from open book exams considerably. Instead of simply looking up disconnected bits of information, students set out to pictorially synthesise a relatively large body of knowledge in a very limited space (usually only a single sheet of white paper). Additionally, the use of words or numbers is not allowed. As a result, students have to focus on the most important concepts that will be assessed and rely solely on their drawing schematics and images. Preliminary studies suggest that cheat sheets can improve student conceptual understanding, increase grades and lower student exam stress (Dickson & Miller, 2005; Erbe, 2007; Song & Thuente, 2015). Such initial findings motivated our selection of cheat sheets as focal pedagogy. Our focus on cheat sheets is also consistent with the fact that drawing allows students to practise visual modes of representation prevalent in the field of science, such as the use of inscriptions for communicating scientific findings. As emphasised by scholars such as Ainsworth et al. (2011) and Binns et al. (2011), science is inherently a visual field of study.

Producing authorised cheat sheets provides students with valuable opportunities to consolidate material in order to develop their own meaning. Restrictions on what can be included on these cheat sheets can further help students familiarise themselves with details of the material and has been found to be successful at both the undergraduate and graduate levels of science education (Song et al., 2016; Song & Thuente, 2015). Previous studies have also proposed the possible need to modify course examinations by adding more higher-order questions so that students cannot rely on cheat sheets simply for the purpose of low-level recall.

Criticism of cheat-sheet use appears only in studies conducted in the context of recall tests with multiple-choice and recall-based questions, resulting in similar results to that of an open-book exam (Dickson & Bauer, 2008). Additionally, low levels of student learning were found when class-collaborative cheat sheets were used instead of personalised individual drawing (Cannonier & Smith, 2019). Nonetheless, when used individually and with appropriately formatted test questions, cheat sheets have been shown to help weaker students improve their academic performance in an undergraduate engineering class (Song & Thuente, 2015).

Despite such caveats, cheat sheets are generally considered a practical and revealing application of Bloom's Taxonomy (Anderson & Krathwohl, 2001) wherein various auditory and visual stimuli provided by the instructor serve as sources of inspiration in the processing, synthesis and creation of pictographic concept representations (Oliveira et al., 2021). In this vein, students that create new ways to represent or interpret concepts are performing at a higher cognitive level (Anderson & Krathwohl, 2001), and need to possess a solid understanding of the taught material in order to be successful in the creation of a cheat sheet. Such a contention is supported by studies such as Potkins (2022) which reports that the average creativity score of students' cheat sheets correlated positively with the grade that the student achieved on the test for which it was used.

METHODOLOGY

The present study adopts a mixed-method research approach (Creswell & Creswell, 2018), relying mainly on descriptive data collected through open-ended research methods such as video-recordings and open drawing. Such a methodological approach is reflective of the challenges inherent to any empirical investigation of creativity, a highly elusive and creative sociocognitive phenomenon (Jackson, 2006; Kahn et al., 2011; Montuori, 2012). By simultaneously quantifying and qualifying student performance of a potentially creative activity (pictographic production), we sought to systematically evaluate the cognitive impact of a carefully designed instructional intervention (adoption of cheat sheets) without reducing its outcomes to decontextualised numbers. Inclusion of a qualitative component allowed our analysis to go beyond simply reporting frequencies and gain a better sense of the cognitive processes and phenomena at play, including original stimuli encountered by students (e.g., images on the instructor's PowerPoint), specific cognitive operations performed by students (e.g., imitative vs. creative thinking), and resulting visual productions (e.g., conceptual drawings). In other words, we sought to better understand students' creative process in its entirety, from cognitive inspiration to visual production.

Participants

Participants in this study were 72 undergraduate students enrolled in a third-year animal behaviour course at a Canadian university. Every student in the class was given the option to engage in the present study, although participation was not mandatory. The course was taught by the second author (henceforth referred to as Author 2) who held a PhD degree in biology and had approximately 14 years of teaching experience at university level. Additionally, Author 2 had an artistic background and held a teaching philosophy that valued creativity as a pedagogical tool. He considered himself to be a creative instructor and was recognised as such by students and colleagues. His *creative teaching mindset* (Harris & de Bruin, 2018) was the main reason behind our selection of his classroom as our research site. As shown by previous research, teachers' beliefs about creativity are essential to the encouragement of creativity within the classroom (Ata-Akturk & Sevimli-Çelik, 2020; Loveless et al., 2006). Effective teachers have been shown to believe that creativity is an essential goal of education (Kasirer & Schnitzer-Meirovich, 2021), that it is possible for most students to grow in their creativity (Kettler et al., 2018; Paek & Sumners, 2017; de Souza Fleith, 2000), and that they are capable of fostering student creativity (i.e., have self-efficacy) (Rubenstein et al., 2013). Author 2 shared all of these beliefs.

Author 2's commitment to creativity was particularly evident in his creative teaching style. Instead of reciting information on slides and using traditional expository teaching methods, the instructor adopted what might be considered ‘unconventional practices’ for an undergraduate science course, such as humorous theatricality, open-ended discussions and creative expression through drawing. As such, his biology class provided us with a unique opportunity to examine student cognition in an educational setting where a science instructor explicitly modelled creative behaviour to his students. As emphasised in the existing literature, instructors need to be prepared to engage in creative pedagogy themselves as students are more likely to emulate creative behaviour when it is demonstrated by the teacher (Grohman & Szmidt, 2013, Soh, 2017). Being a model, coach and guide for student creativity is an essential part of creative pedagogy (Ata-Akturk & Sevimli-Çelik, 2020; Beghetto & Kaufman, 2014; Harris & de Bruin, 2018; Loveless et al., 2006).

Course format and content

Aimed at introducing undergraduate biology majors to the scientific study of animal behaviour, this 13-week course focused primarily on the ecological and evolutionary causes and consequences of a variety of animal behaviours such as communication, altruism and sociality, territoriality, aggression, feeding habits, mating systems and parental care. The course met twice per week for a total of approximately 1.5 hours. During these meetings, Author 2 typically used PowerPoint slideshows to engage students in the discussion of examples of animal behaviour. However, rather than engaging in a one-sided lecture, what ensued were lively discussions wherein examples of animal behaviour were creatively explored through means such as dramatic and often comedic demonstrations of the studied behaviours (e.g., mirthful meaning-making). Students were provided with an open space to collaboratively explore the field of animal behaviour and were encouraged to express themselves freely without the fear of negative reception. Students were supported in their individual analysis of ideas and provided with the opportunity to merge their own creative process with critical thinking (Averil et al., 2001; Garner, 2007). This has been shown to be key in developing creativity (Razumnikova, 2012; Sawyer, 2011). For more detailed information about the content and pedagogical format of this class see Oliveira et al. (2018, 2020).

In conjunction with his unconventional approach to science instruction, students were offered the opportunity to independently create cheat sheets for two midterms and the final exam. Students were permitted to develop a one-page cheat sheet to be used during course examinations. The only caveat was that students' cheat sheets were not to contain any words or numbers, limiting the content of the cheat sheets to hand-drawn sketches, symbols or drawings. Methods of drawing were left to the students, including the option to use colour. There were no limitations on the quantity of drawings that were allowed, as long as it fit on a single page. Following Author 2's neutral suggestion and direction, the students that opted into this approach synthesised a wide variety of concepts into summative drawings on these pages, with open-ended and unprompted creativity.

Data collection

The present study relied on multiple sources of data to answer the aforementioned research questions. First, at the end of every exam, cheat sheets produced by students were collected and anonymised. A total of 48 cheat sheets were collected during the course of the term (23 for Midterm 1, 15 for Midterm 2, and 10 for the Final exam). Additionally, the entire course was video-recorded and analysed as a pedagogical artefact used for instruction (PowerPoint slideshows). This multiple means of data collection is a direct reflection of the complex and multifaceted nature of human engagement with visual representation.

In alignment with previous investigations of visual records of human cognition (Collier, 2001; Okada & Ishibashi, 2017; van Leeuwen & Jewitt, 2001), we sought to make a systematic inventory of students' drawings as well as the images that may have served as a source of inspiration for their work. As previous cognitive studies have shown (e.g., Okada & Ishibashi, 2017), one's visual production can be strongly influenced by others' creative work, thus making imitation an important part of the creative cognitive process. This was the main reason behind our decision to also systematically document the visual and verbal stimuli to which students were exposed in class (images shown by the instructor, ideas discussed in class, etc.). By doing so, we were able to analytically examine the extent to which students' visual representations constituted creative departures from the imagery with which they were presented during course instruction.

Our focus on cheat sheets is also consistent with the existing research. Like previous studies, we relied on a drawing task that was open-ended both in terms of content and form. Our work shares similarities with Droodles (Price et al., 2000) as well as 'draw-a-scientist' tests (Losh et al., 2008), commonly used methods of data collection wherein participants are provided with open-ended prompts to perform visual acts (draw pictures of their choice about particular concepts). As freely externalised representations of a mental concept/cognitive state, these drawings visually depict the individual students' personal interpretation of a particular concept. Likewise, in the present study, images drawn by students are considered *cognitive signifiers*—symbols that 'stand for' their individual understandings of a particular biological concept presented as part of the course delivery. Due to the openness of the visual production, students have the option of creatively externalising these cognitive signifiers (i.e., externalisation of their thinking can be characterised by varied degrees of creativity).

Data analysis

Overall, researchers spent approximately 210 hours (from September 2021 to February 2022) conducting a visual design analysis of the 48 student cheat sheets. Visual design analysis refers to the systematic examination of the semiotic ways in which pictorial representations represent and communicate meanings (Kress & van Leeuwen, 2006). This analysis was divided into phases as described below.

Analytical Phase 1

To identify the different forms of creative cognition performed by students as a result of the introduction of cheat sheets into the biology course (Question 1), we conducted a preliminary qualitative comparative analysis of students' drawings. Using Microsoft PowerPoint, each individual cheat sheet was first placed on a separate slide. Each cheat sheet then underwent a process of *concept boxing* whereby drawings of specific concepts covered in the course were identified and visually demarcated through the addition of boxes (Figure 2). This systematic segmentation into smaller visual units (*individual concept drawings*) rendered the complex visual field of cheat sheets more amenable to systematic analysis. Concept boxing was performed through careful consideration of the negative space (blank areas) between visual elements or by simply following the drawer's original segmentation. For example, some students chose to draw their cheat sheets as a collection of boxed-in visual components completely separated by lines. Each individual concept drawing was also assigned a label that indicated the course examination for which it was constructed (M1 = Midterm 1, M2 = Midterm, and F = Final examination) and a page number (e.g., P1). Moreover, researchers hyperlinked individual concept drawings to their respective PowerPoint pres-

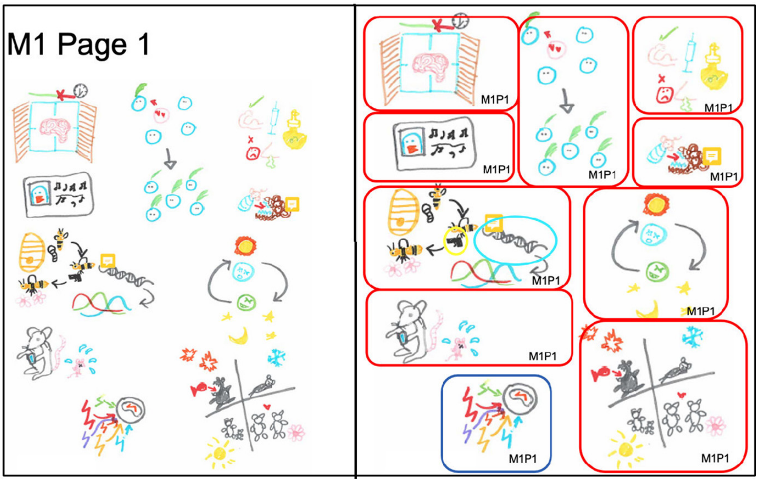


FIGURE 2 Concept boxing process used to break original cheat sheets (left) into individual concept drawings (right).

entation from the instructor's materials. This analytical process generated a total of 518 individual concept drawings across the 48 cheat sheets created by students during the entirety of the biology course.

Additionally, as part of our qualitative analysis, single concepts (images, slides, etc.) were pulled from the instructor's PowerPoint presentations and placed side-by-side with their respective individual concept drawings from students' cheat sheets, forming *image sets* (Figure 3). Once formed, image sets were then assessed in terms of the relative degree of divergence associated with each concept collectively across students' cheat sheets. Image sets with a high degree of similarity (e.g., several students using the same symbols) were considered as having a low degree of cognitive divergence (i.e., being characterised by a single line of thought or interpretation). In contrast, image sets with unique imagery were viewed as having a high degree of divergent thinking (i.e., being characterised by independent lines of thought and multiple concept interpretations). Such a focus on divergent production (Guilford, 1950) was aimed at the identification of student engagement in two additional types of student cognition, namely divergent and convergent thinking.

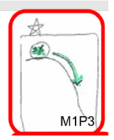
Analytical Phase 2

In this second phase, our preliminary qualitative analysis of student cognition was expanded into a quantitative analysis of student performance. Once concept boxing of students' cheat sheets was finalised, individual concept drawings were analytically interpreted in light of the performance continuum of student creative thinking (Figure 1). As part of this process, each individual concept drawing was copied and pasted into a Microsoft Excel spreadsheet and then comparatively examined in relation to the PowerPoint imagery from instructional materials and classroom discussions (Table 1). Attention was given specifically to the cognitive operations performed by students, that is, whether they reproduced, modified, combined or created new images/ideas. The objective of this spreadsheet was to give every individually identified concept a Nilsson score of creativity. The Nilsson scoring criteria was fitted to our study and followed the overall structure of Nilsson's Taxonomy of creative design (Nilsson, 2011).

Nilsson's taxonomical approach to the subject categorises creativity into five tiers to which we added point values as follows: Uncreative Imitation (Score = 1), Variation (Score = 2), Combination (Score = 3), Transformation (Score = 4) and Original Creation (Score = 5). According to our classification criteria, a score of 5 would indicate that the student's concept drawing was depicted in their own visual language and did not repro-

FIGURE 3 Example of an image set with instructor's slide of the concept ‘Single Gene Effects’ (left) placed alongside student drawings cut and pasted from the cheat sheets of three different students.

TABLE 1 Sample page from coding book

	Concept	Slide No.	Cheat sheet No.	Level of creative cognition
	What is behaviour	51	3	Original creation
	Darwin	52	3	Transformation
	Skinner and Hebb	53	3	Transformation
	Lady Bug Example	54	4	Variation
	Lady Bug Example	54	18	Combination
	Tinbergen's 4 Questions	55	3	Transformation
	Tinbergen's 4 Questions	55	3	Transformation

duce any part of the content displayed in class. If a drawing was given the lowest score of 1, it would indicate that the student's drawing was an exact replication of an image or graph presented in class. Scores were given only in whole numbers. All scoring was independently completed by at least two researchers to ensure inter-rater reliability. Any drawings that received different scores were then discussed between researchers to achieve a mutual final score. All scoring was also performed twice between a single researcher to ensure intra-rater reliability.

It is important to note that not all drawings on the cheat sheets could be identified. Despite the many hours that were put into the decoding process, many students drew their cheat sheets using their own visual language or symbols, hence making it near impossible for the researchers to decipher its true context. Out of the 25 cheat sheets that were used during this study, the researchers found that they contained a total of 491 concepts across all sheets. Of that total, only 210 concepts were positively decoded.

RESULTS

Question 1: Forms of student creative cognition

Overall, it was found that students' creative cognition varied considerably both in terms of the performance level and degree of divergence. These findings are elaborated upon below.

Level of creativity

With regard to performance level, our qualitative analysis revealed that students' cheat sheets represented all five different types of creative cognition in our proposed theoretical spectrum (Figure 1). As the following examples show, student work included examples of reproduction, modification, combination, transformation, as well as creation.

Figure 4a contains the PowerPoint slide used by the course instructor to introduce the concept of sensory bias, which is the concept that different animals perceive the world in varying ways. The slide shows two images, one of how humans perceive flowers (left)

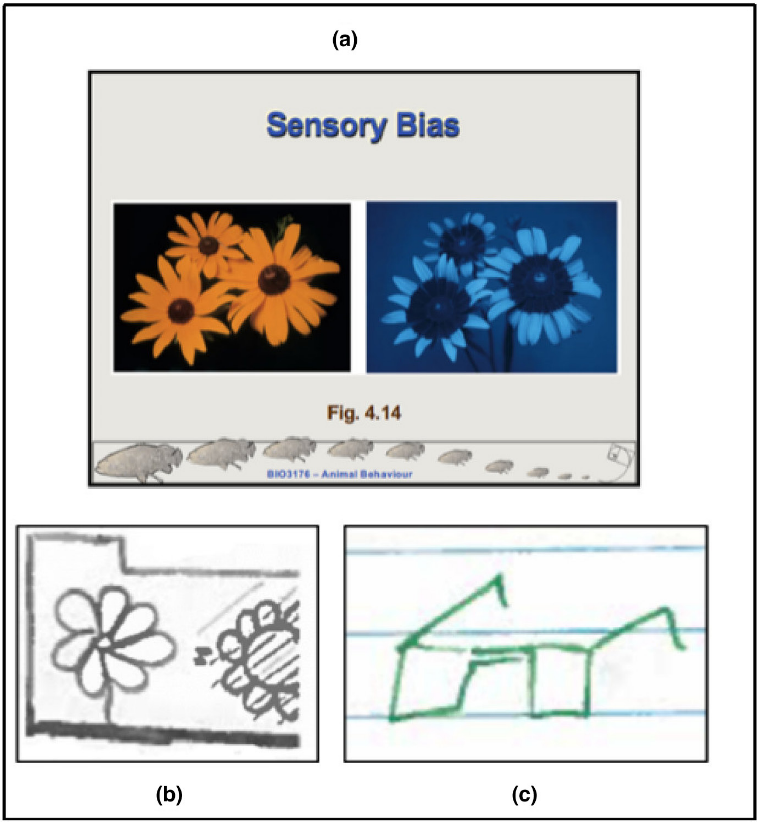


FIGURE 4 (a) Instructor's slide on the concept of sensory bias; (b) Student *variation* drawing of same concept; and (c) Student *original creation* drawing of the same concept.

and another of how bees perceive the same flowers (right). Students took very different approaches to drawing this concept in their cheat sheets. One student drew a near exact replica of the flowers, with the small addition of an equal sign between the flowers to signify that they are the same (Figure 4b). This small embellishment indicates that she performed at the cognitive level of *variation*. Another student chose to draw a pair of glasses, generating the metaphor that different animals 'see' the world through different lenses (Figure 4c). This is a sophisticated example of *original creation* in this study, the use of metaphor to capture the concept represented on the instructor's slide without reproducing any part of the original image is a sophisticated example of original creation within this study.

Figure 5a contains a slide shown by the course instructor to illustrate the biological concept that environmental factors can affect the behaviours of animals. More specifically, it shows that, although kangaroo rats usually prefer to forage when it is darkest out (at night without the full moon), they switch to foraging at any time when food becomes scarce. The scale on the left side of the slide shows at what times during the year the kangaroo rat strategy changes. Again, students took contrasting approaches to representing this concept on their sheets. One student copied the figure exactly as it was shown on the instructor slide, demonstrating the cognitive form of *replication* (Figure 5b). In contrast, another student chose to visually depict the ideal foraging time for the kangaroo rat (Figure 5c)—a concept discussed in class but not directly represented on the instructor's slide, thus making this an example of *transformation* (turning verbal information into a visual medium).

Figure 6a contains several PowerPoint slides used by the instructor while teaching the concept of *code breaking*—when one animal takes advantage of another animal's instinctive behaviour. The animal who is 'breaking the code' gains benefits whereas the one whose 'code is being broken' is impacted negatively. This concept was presented over a series of slides with different examples of code breaking on each one, one involving butterflies and ants, another with bees and beetle larvae, and the last with two species of birds. Again, this biological concept was visually represented in varied ways by students on their cheat sheets. One student created a separate *reproduction* for each of these examples (Figure 6b). It is noticeable that this student draws lines around each individual concept on their cheat sheet, clearly separating them from each other as well as other drawings unrelated to code breaking; no effort was made to combine these images together. This is in sharp contrast

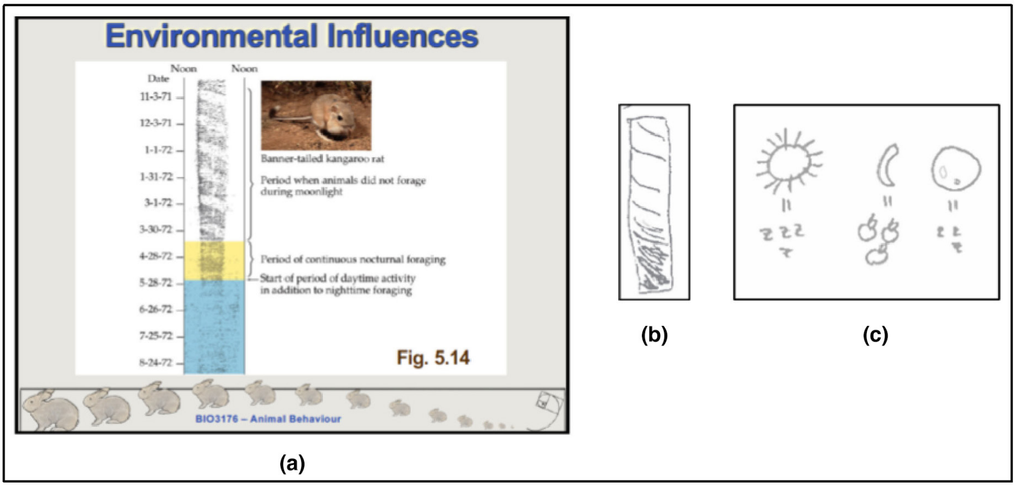


FIGURE 5 (a) Instructor's slide on the concept of environmental influences on foraging behaviours of the kangaroo rat; (b) Student *reproduction* drawing of the same concept; and (c) Student *transformation* drawing of the same concept.

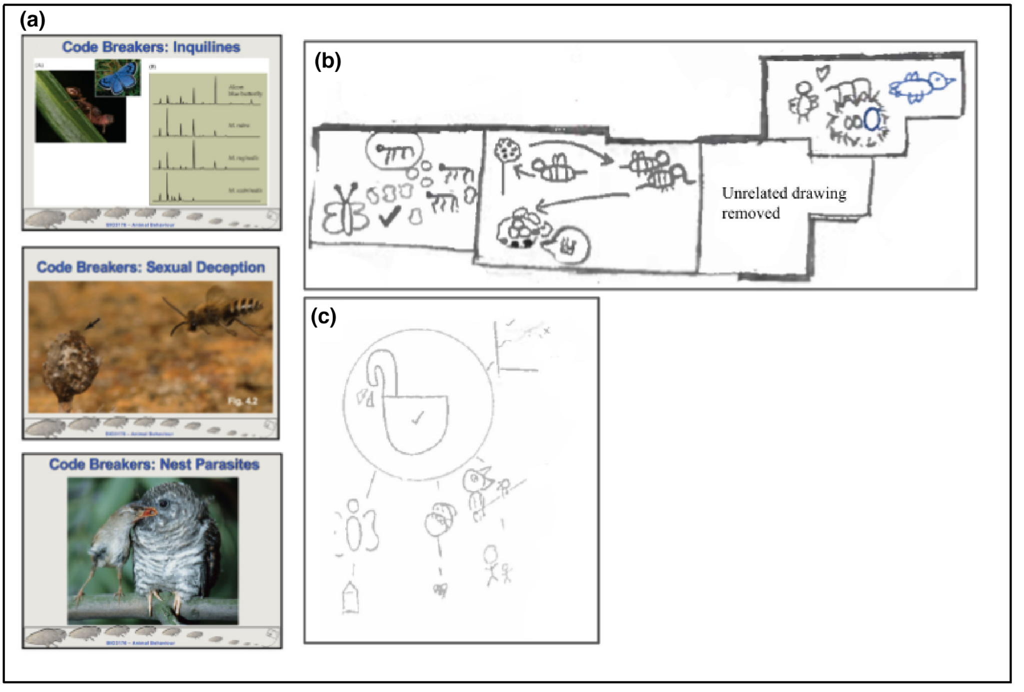


FIGURE 6 (a) Instructor's three PowerPoint slides on concept of code breaking; (b) Student's three separate reproduction drawings for each slide on same concept; and (c) Student *combination* drawing of same concept.

to another student's drawing who chose to combine all three examples into one piece with a ‘mind map’ style drawing (Figure 6c). In this particular drawing, various smaller visual elements stem from a bubble with a large broken lock, a metaphor for ‘code breaking’. Additionally, a small graph is depicted in the upper-right hand corner showing the costs and benefit breakdown of code breaking. By bringing all these disparate ideas into one drawing, this student demonstrated *combination*.

In sum, we discovered that student creative cognition as a result of pedagogical use of cheat sheets spanned the entire spectrum of creative performance. Instead of being predominantly imitative (i.e., limited to reproduction), students performed a variety of increasingly demanding cognitive acts that included modification, combination, transformation and creation.

Cognitive divergence

Generally speaking, our qualitative analysis revealed that student performance of divergent thinking varied considerably depending on the specific concept being visually represented in drawing. This is evident in Figure 7a, which contains a PowerPoint slide used by the course instructor to teach the biological concept of *honest signalling*—how the diversity of songs a male bird produces acts as an honest signal to the female bird of his quality. As depicted in Figures 7b–j, the original image was subsequently drawn by a large number of students in ways that were surprisingly varied (i.e., divergent). Although they all demonstrated the same categorisation of creativity (*transformation*), their representational approaches varied significantly, with some students favouring symbolic drawing outlining the abstract ideas

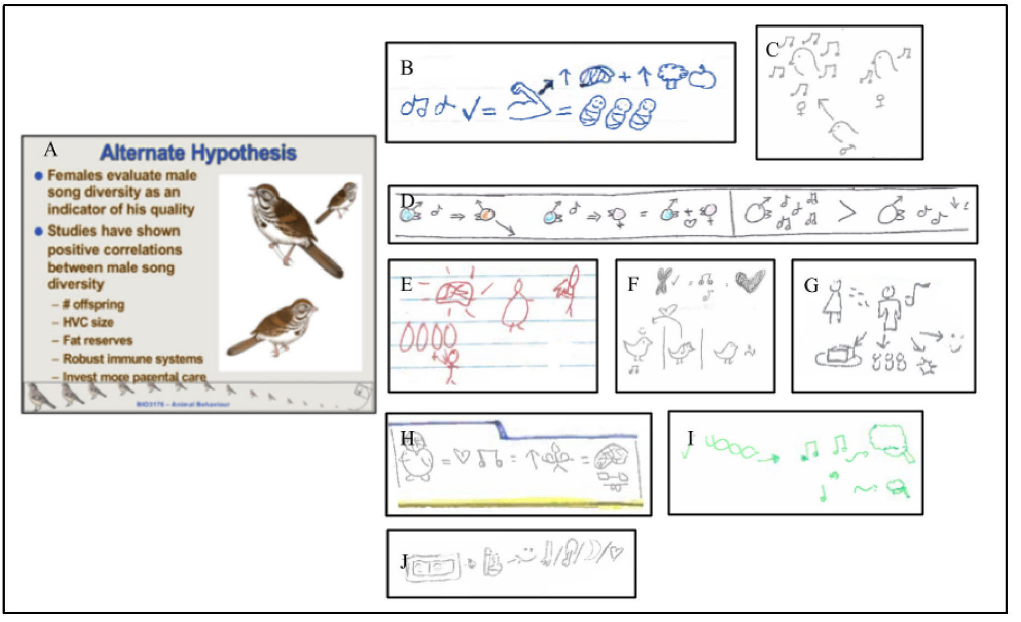


FIGURE 7 (a) PowerPoint slide on concept of male bird song diversity as an indicator of quality; (b–j) Various student drawings of same concept.

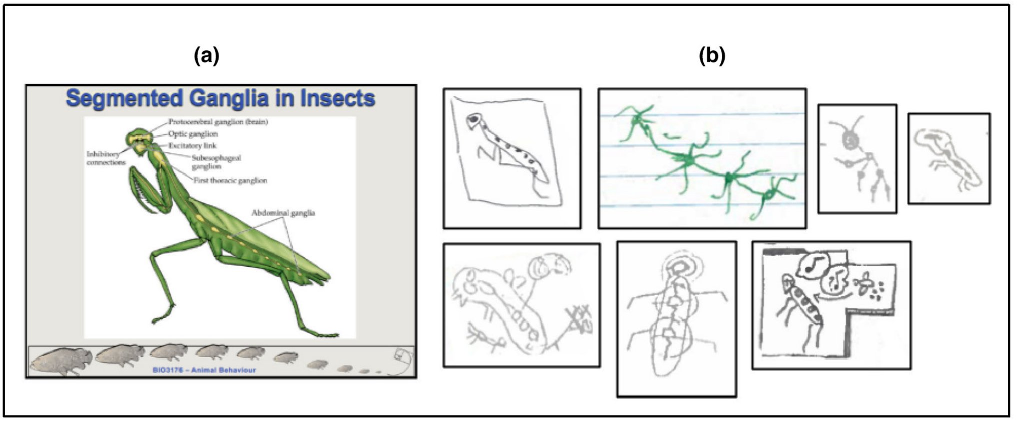


FIGURE 8 (a) Instructor's slide on the concept of segmented ganglia in insects; and (b) Various student drawings of the same concept.

presented, whereas others choosing more literals interpretations of the concept focused on the bird itself.

In contrast, other images on the instructor's PowerPoint slideshow seemed to trigger more uniform visual performances from students. This alternative trend is illustrated in Figure 8a, which contains a slide demonstrating the concept of segmented ganglia (a morphological feature that many insects possess) through the example of a mantis. Most corresponding student drawings are either *reproductions* or *variations* of the original slide (Figure 8b). Only one student created a slightly more abstract drawing of the ganglia devoid of the mantis (seen in green).

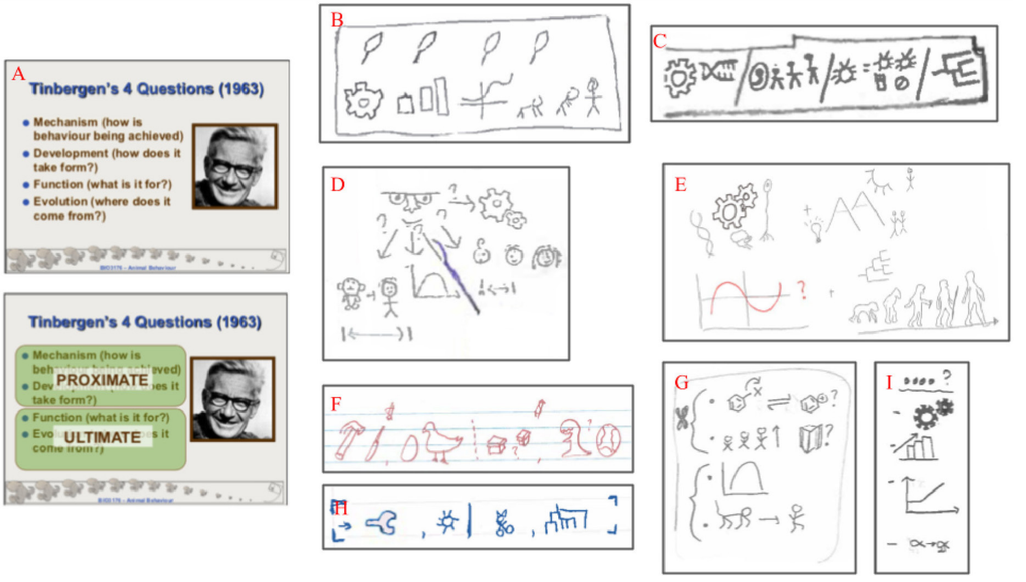


FIGURE 9 (a) Instructor's slides on concept of Tinbergen's four questions; and (b–i) Various student drawings of the same concept.

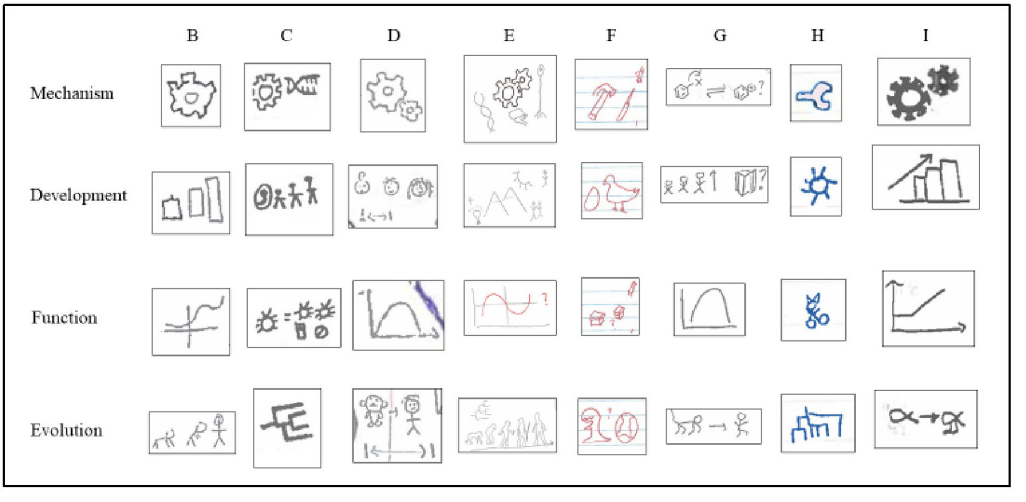


FIGURE 10 Student pictograms seen in Figure 9 broken down for each of Tinbergen's four questions: mechanism, development, function, evolution.

Both Figures 9 and 10 focus on the concept of Tinbergen's four questions. These questions serve as a framework for the different levels of understanding animal behaviour, being divided into two categories: proximate (the 'how') and ultimate (the 'why'). The proximate questions are those of mechanism (how is behaviour being achieved) and development (how does it take form), and the ultimate questions are those of function (what is it for) and evolution (where does it come from). While the only image on the instructor's PowerPoint slide is a portrait of Tinbergen himself, many students chose to depict Tinbergen's four questions as one pictograph with four parts (Figure 11b–i), at times clearly separated by lines.

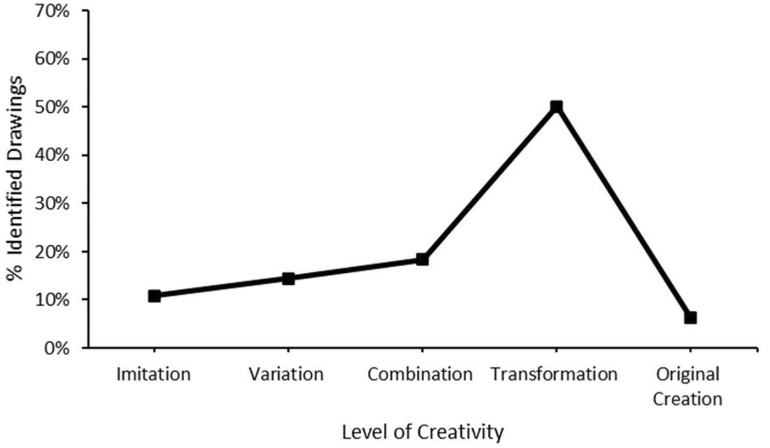


FIGURE 11 Percentages of student creative performance across all student drawings (N = 518).

TABLE 2 Overall distribution of students' levels of creative cognition (N = 518)

Performance level	Frequency	Percentage
Imitation	56	11
Variation	75	15
Combination	95	18
Transformation	260	50
Original creation	32	6
Total	518	100

In Figure 10, each student drawing is broken down into its four parts and identified as one of the four questions: mechanism, development, function, evolution. This allows for a direct comparison of the individual symbols and their meanings. It is noticeable that some parts of this concept are depicted more diversely than others. ‘Function’ is dominated by drawings of graphs (i.e., a mathematical function) in five out of eight student drawings (B, D, E, G, I). ‘Mechanism’ is dominated by drawings of metaphorical gears in five out of eight student drawings (B, C, D, E, I). Additionally, two of the students drew both gears and a DNA strand (C and E). ‘Evolution’ is dominated by monkey-to-human progressions or a *fish to fish-with-legs* progression in five out of eight student drawings (B, D, E, G, I). Two other students drew a taxonomic tree (C and H). In contrast, ‘development’ is much more diverse in symbols; two students drew a bar graph (B and I), three others drew a progression from a baby to an adult (C, D, G), and three drawings did not display any similarity to others (E, F, H).

Looking at Figure 10, it is also apparent that some students created more unique symbols across all four concepts. Looking specifically at student F we can see that all of his drawings are unique (4/4), and that student H also has a majority of unique drawings (3/4). On the other hand, students B and I created nearly identical symbols to each other for all four concepts.

In conclusion, production of cheat sheets gave rise to divergent as well as convergent types of creative cognition. While some image sets were characterised by unique symbology (different symbols were used by different students across cheat sheets), others contained symbols with a high degree of similarities (the same symbols were used by different students across cheat sheets).

Question 2: Cheat sheet effectiveness

Our quantitative findings revealed that student creativity was predominantly at the level of transformation (50%), being followed by combination (18%) and variation (15%) (Table 2 and Figure 11). Put differently, student cognition during construction of cheat sheets dealt mainly with modification of the ideas and images encountered during the course. While constructing their cheat sheets, students most often changed the medium of an idea discussed in class, combined ideas/images, or simply embellished an image shown by the instructor. In contrast, the least frequent performance levels were original creation (6%) and imitation (11%). Surprisingly, exact reproduction of images was almost as infrequent as creation of completely novel images. Such trends provide evidence that the instructor's cheat sheet pedagogy was particularly effective in promoting intermediate levels of student creative cognition. Nonetheless, its effectiveness in promoting original creation seems limited as evidenced by student production of only six drawings categorised as original ideas.

In sum, instructor adoption of the cheat sheets promoted a shift toward the creative end of the cognitive performance spectrum. Instructor adoption of cheat sheets was effective in encouraging students to go beyond reproduction of scientific concepts and cognitively perform intermediate levels of creative modification of pre-existing ideas and/or images.

DISCUSSION

Integration of scientific content instruction with creative drawing can give rise to a wide spectrum of student cognition at the higher education level (i.e., diversity of thought). This integrated approach gives students the opportunity to go beyond mere replication of concepts and perform various types of cognitive operations, including modification, combination, transformation and creation of novel ideas. The significance of these findings is now considered.

Structured imagination

One important trend in our findings was that student creative cognitive performance as a result of their engagement in pictographic production was predominantly at intermediary levels. As reported above, 83% of all individual concept drawings involved creatively altering ideas and images encountered during the course, with students changing the medium of an idea discussed in class, combining images together, or modifying an image shown by the instructor. In contrast, creation of completely original and novel images was considerably less frequent, encompassing only 6% of individual concept drawings.

The above finding is consistent with empirical and theoretical work from the field of cognitive psychology where scientific creativity has been conceived as a form of *structured imagination* (Ward, 1994). This literature emphasises the notion that scientific creativity is constrained (structured) by prior knowledge, ontological expectations and intuitive assumptions (Simonton, 2003). Rather than being limitless and unconstrained, scientists and engineers' creative work is guided by existing knowledge as evident in their tendency to revise and improve known ideas (e.g., development of new technological devices with a high degree of resemblance to older designs, etc.). Because existing conceptual space may serve to constrain scientists' creative work and bias their thinking, radical innovation or restructuring is relatively infrequent throughout the history of science compared to alteration of known ideas. As De Cruz and De Smedt (2010) write, 'scientific creativity mostly works with small incremental steps, rather than revolutionary leaps' (p. 42). Overcoming such cognitive constraints usually involves distant analogical and metaphorical thinking.

Looked at from the above perspective, the predominance of intermediary levels of creativity in the present study is indicative of student practice and development of structured imagination. Rather than being free to completely reimagine science concepts, students' creativity was limited by the existing conceptual space in the field of animal behaviour and largely narrowed to the structured reimagination of ideas to which they were introduced in class. Nonetheless, students, at times, managed to overcome these constraints and produce radically novel visual representations (unstructured reinvention of ideas) through the use of analogies and metaphors (e.g., animal vision as glasses, code breaking as broken lock, biological mechanisms as gears). As they do for professional scientists, these analogies and metaphors provided students with a powerful epistemic tool to break free from existing conceptual structures and think about animal behaviour in novel and divergent ways. Rather than being completely constrained by the scientific knowledge learned in class, students' thinking about animal behaviour became characterised by a certain degree of *cognitive fluidity* (De Cruz & De Smedt, 2010), an important aspect of creativity development. As such, drawing cheat sheets afforded students a chance to practise metaphoric/analogical thinking, hence potentially developing their scientific creativity.

Imitation and inspiration

Although exact reproduction of images was relatively infrequent (11% of individual concept drawings), imitation remained an important part of student cognition. As evident in the high degree of resemblance between the instructor's original images and students' subsequent drawings, student performance of intermediary levels of creativity (modification, combination and transformation) still included a noticeable degree of imitation. Student creativity was not completely devoid of imitation.

This apparent persistence of imitation in student work is consistent with research showing that imitation constitutes an important source of inspiration for original and innovative creation (Okada & Ishibashi, 2017). Imitation of others' creative work allows novices to experience *cognitive relaxation*. Research shows that students who set out to make exact reproductions of others' visual work tend to become more relaxed over time when the work being reproduced resonates with their personal experiences, background and interests (i.e., when the work 'speaks' to the viewer) (Jackson et al., 2006; Okada & Ishibashi, 2017). As their cognitive constraints become more relaxed, reproduction becomes more flexible (less focused on precise replication), and students begin to allow themselves to alter ideas in creative and original ways. Students gradually take creative freedom to innovatively play with ideas while representing them in a pictographic format—a form of *cognitive tinkering*.

A similar process was 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 visually represent concepts of animal behaviour in original and individualised ways. When this happened, students' cognitive constraints on the representation of animal behaviour became more relaxed, leading to higher levels of cognitive divergence, as evident in the occurrence of unique symbology (student use of unique symbols) across cheat sheets. Depending on the creative stimuli available in the classroom at the time of learning, some concepts seemed to resonate with students at a personal level more than others. In other words, some concepts presented by the instructors promoted *cognitive playfulness* (Tan & McWilliam, 2008), thus inspiring student creative work that was not only creative (novel compared to the original images seen in class) but also unique (different from those of other students). Further research is needed to determine the exact features of concepts whose exposure by the instructor may have triggered such increased inspiration among students.

Pedagogical effectiveness

Based on the reported findings, we considered cheat sheets to be generally effective as a pedagogical tool for promoting creative learning of scientific content. Performance of this open-ended drawing exercise effectively encouraged students to metaphorically and analogically 'play' with science concepts learned in class, a cognitive activity consistent with scholarly accounts of professional scientific creativity (De Cruz & De Smedt, 2010).

Careful consideration must also be given to the high stakes and potentially stressful nature of course assessments during which cheat sheets were to be used. Course examinations are stressful times within a term as they take place within a limited stretch of time and can impact students' final grades. This high-stakes context places more pressure on students to make drawings that will best situate themselves to perform well on examinations. Such pressure may have inadvertently affected students' creativity when designing and drawing their cheat sheets. As research has shown, stress can impact one's creative abilities (Gulzhaina et al., 2019). For instance, creating completely novel symbols with no resemblance to learned ideas/imagery could have come with the cost of reduced mnemonic value (i.e., made it harder for students to recall visually represented concepts in their cheat sheets). As such, students' intermediary levels of creativity could have been strategic rather than merely a reflection of their inspiration. Students' drawing of ideas/images that were only partially altered could have been aimed at maximising cheat sheets' utility as a means to retrieve mentally stored information and ensure a high grade, as opposed to an uninterested instantiation of creative expression.

Another important factor that should be taken into account is instructor modelling. As our results show, effectively promoting creativity in science classrooms entails more than simply having students create cheat sheets; adoption of cheat sheets is only part of the equation. Other essential factors must be present, such as instructor modelling, a supportive classroom atmosphere, and so on. Far from being a panacea, cheat sheets' effectiveness as a means to promote creativity among science students is likely to depend upon context.

CONCLUSION

In conclusion, the present study underscores the pedagogical value of authorised cheat sheets as a means to promote students' creative expression while learning scientific content. It lends way to the belief that implementing opportunities and space for undergraduate students to creatively express themselves can encourage higher-level, diverse learning that would lead them to create or generate new ideas based on class material. Our findings also underscore the fact that creative ideas in science do not spring up in a vacuum; the act of creating something novel requires conceptual knowledge, pedagogical support and, most importantly, inspiration. This is consistent with Milne's (2020) characterisation of creativity as a collision of imagination and knowledge, generating ideas or making connections between the known and unknown. As such, the present study helps advance our current understanding of how students' creative abilities can be fostered in the context of an undergraduate biology course. In spite of this fact, further research would need to be conducted to better understand how a student's creative performance may improve or decline over time (i.e., to illuminate students' trajectories of creativity development). Future studies would also benefit from a larger sample size, application of probabilistic models of measuring student creativity, and inclusion of additional methods of triangulation, such as member checking. Lastly, since the focus of our study was on behavioural biology, a largely observational science, our findings may not be generalisable to the physical sciences, particularly those fields where abstract concepts are more prevalent (e.g., theoretical physics) as well as those that rely more heavily on experimentation (e.g., chemistry). It is our hope that this study will act as a predecessor for future studies on the topic, helping educators and researchers develop an improved understanding of the relationship between pedagogical tools in a science classroom and students' emergent creativity.

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CONFLICT OF INTEREST

The authors have no relevant financial or non-financial interests to disclose.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

ETHICAL APPROVAL

The authors declare that this project received IRB approval at the University of Ottawa.

INFORMED CONSENT

The authors declare that informed consent was obtained from all participants.

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