Exploring the Value of Drawing in Learning and Assessment

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Abstract: Drawing is increasingly recognized as a literacy of science. It is claimed that when learners draw they engage in ways that help them evaluate and transform their understanding, practice fundamental disciplinary practices and provides the basis for formative or summative assessment. This symposium draws together research on student drawing across different disciplines (e.g. Chemistry, Biology, and Anatomy) to explore the value that drawing can have in learning science and medicine. Importantly, the papers take a nuanced view of the value of drawing; attempting to avoid the sometimes overblown claims that accompany calls for particular approaches to education by addressing situations when drawing has been found to be ineffective as well as helpful. They will also focus on analysis of process data (e.g. drawings) to provide insight into when particular representational practices are helpful and how they must be executed and supported to gain these benefits.

Introduction

It is well accepted that a range of disciplinary practices underpins a working understanding of scientific knowledge. We argue with others (e.g. Ainsworth, Prain & Tytler, 2011; Lemke, 2004) that drawing is an important disciplinary practice in science and medicine. Drawing plays a number of important roles as scientists work and as students learn. For example, analyses of the processes involved in science discovery has shown that scientists draw to transform their understanding (Gooding, 2004). Epistemic practices in the sciences entail reasoning about relationships between multiple, multi-modal representations including drawings, material instruments and phenomena (Nersessian, 2008). Students need to learn how to reason through visual, linguistic and mathematical modes to generate, coordinate and critique evidence and this often involves models and model- based justification (Lehrer & Schauble, 2006). Drawing can support communication between colleagues as they participate in the day-to-day activities of science (Kozma, Chin, Russell, & Marx, 2000) or in a range of formal or informal assessments (Cooper, Williams, & Underwood, 2015). However, the rationale for including drawing differs across disciplines as does the way that drawing activities unfold. Consequently, this symposium explores how students in science and medicine use drawing in similar and unique ways.

Stieff and DeSutter explore the value of adding drawing activities for promoting learning when students engage with dynamic visualizations in chemistry. Students drew up to six times – each time creating an observation sketch of the simulation and reflective sketch of their new understanding. These students were compared to students who followed the same curriculum but did not draw. They found a small but significant effect of drawing and that students who drew more frequently learnt more. Panagiotopoulos and colleagues explore medical students drawing when they learn anatomy in pre-clinical dissection classes. They asked beginning students to draw pre and post dissection and compared these drawings to third years on clinical placement. Their research suggests that students come with expectations strongly formed by textbooks and popular culture, especially for familiar organs such as the heart. Dissection activities, if anything, seemed to destabilize their understanding without replacing it with anything more correct. However, by the third year their drawings showed an increased understanding of the overall shape of the heart although this did come at the cost of specific knowledge of its features. Tytler and Prain present findings from their on-going exploration of the roles of representation construction, including drawing, across a range of school science topics. Their work describes how students use drawing in diverse ways to support their learning and reasoning. Moreover, by comparing the situations where drawing was found to be helpful to those where it was not, they provide guidance for how to use drawing in the classroom. Van Joolingen et al describe an innovative approach to modeling in science. Students created an executable model to express their understanding of scientific phenomenon. However, rather than using complex algebraic expression or artificial graphical formulisms they simply draw the model in a microworld, which the system interprets and animates according to the behaviour described in the model. This paper presents a study of secondary school students learning evolutionary biology through drawing based modelling and reveals how the design of tools, as well as the way students were prepared strongly influenced the effectiveness of this approach.

These papers share the view that drawing can be valuable but illustrate important differences. They combine experiments, ethnographic study and design-based research to understand drawing in learning. By presenting these papers together, we address a number of important points. The first concerns what these students were drawing: from anatomical structures through simulations, models, experiences and abstractions. Drawing was used in assessment, communication, in classroom and as homework. Together they illustrate the ways that drawing is used to support the learning of many different aspects of science and medicine and their assessment. This provides the opportunity to consider if there are distinct disciplinary differences in the ways that drawing should be considered. A second important issue raised is how drawings should be analyzed and what information we need beyond the drawing to analyze the approach. Stieff and DeSutter count the number of drawings and relate them to test scores whereas van Joolingen et al explore the talk around the drawings, Panagiotopoulos et al analyze 10 distinct aspects of each drawing and Tytler and Prain capture video data of the process of drawing to learn in classrooms. Understanding that drawing is an authentic practice in many domains has only recently been widely accepted in the learning sciences and as a result compared to such practices as argumentation and writing, we do not yet have much knowledge about how to study and code the process of drawing and the drawings that result. All participants will make their approach explicit so that with the help of the discussant and audience we can improve our knowledge. Another issue that all participants' address is to consider when drawing or approaches to drawing are **not** helpful. The path of over-excited claims about the benefits of an approach to learning followed by a retrenchment as the evidence does not support those claims is a familiar one. By focusing on the situations when drawing has not been shown to be effective we hope to avoid this path and make our approaches more nuanced from the beginning. Our discussant Puntambekar will contrast these four perspectives to help as achieve a better position to appreciate the costs and benefits involved in using drawing in learning and assessment, as well the challenges for researchers to understand these activities and how best to enact them.

Drawing from dynamic visualizations

Mike Stieff and Dane DeSutter

Recent reviews regarding drawing to learn (Van Meter & Firetto, 2013; Waldrip & Prain, 2012) have reported few studies that investigate the efficacy of drawing activities in STEM classrooms, and the results of these studies have been varied. Such work suggests that drawing can be beneficial for science learning, but empirical studies demonstrating when drawing supports STEM learning and how to capitalize on the benefits of drawing remain outstanding. Notwithstanding the limited evidence, recent innovations for teaching science have begun to integrate drawing activities more centrally into curricula that include complex dynamic visualizations, such as animations and simulations. Dynamic visualizations direct learners' attention to information that is typically not present in texts or illustrations and the extent to which drawing activities support, replace, or enhance learning from visualizations is unknown. Moreover, there is some empirical evidence that drawing activities may not effectively support learning from dynamic visualizations any more than other instructional scaffolds. For example, studies regarding learning in high school chemistry classrooms (Stieff, 2011; Zhang & Linn, 2011) have reported marginal effects of coupling drawing with dynamic visualizations compared to activities that do not involve drawing. More recently, Zhang and Linn (2013) reported that drawing is no more effective than activities that involve simply selecting information presented in a visualization. Here, we report on the results of a large-scale efficacy study that compared the impact of Connected Chemistry Curriculum (CCC) activities that couple dynamic visualizations with drawing activities to learning activities without visualizations or drawing. 92 students (drawing group) completed six one-hour CCC homework activities during their normal course of instruction in an undergraduate general chemistry course, and 413 students learned the same content without using the CCC activities (problem solving group). The CCC activities involved students engaging with a dynamic simulation of molecular behavior to investigate a core disciplinary concept. Students sketched at least twice while completing a guided inquiry investigation using a CCC simulation. Students completed an *observational sketch* that represented what they viewed in the simulation; Students then completed a *reflective sketch* that represented their mental model of a novel chemical system after completing the activity (Figure 1). Activities were administered approximately every three weeks over a four-month period and completed individually. Participants in the problem-solving group completed an algorithmic problem solving worksheet related to the six concepts targeted by the CCC activities.

Figure 1. An observational (LHS) and reflective sketch (RHS). The activity moves from observational sketches of a closed gaseous system to reflective sketches of an unknown gas under two conditions.

Learning outcomes were assessed with a 22-item fixed-choice achievement assessment developed by the ACS (American Chemical Society, 2001) that students completed on the first and last day of instruction. Learning outcomes were analyzed using repeated-measures ANOVA with college GPA included as a covariate. The analysis revealed a significant difference between groups ($F(1, 500) = 4.89$, $p = .027$, $h_p^2 = .01$) with students in the drawing group ($M = 9.87$, $SD = 5.8$) slightly outperforming students in the problem solving group ($M = 9.24$, $SD = 2.7$). To isolate the contribution of sketching activities to learning in the drawing group, we performed a parametric linear regression in the Bayesian framework. We chose a non-informative prior distribution, given no prior knowledge of the true parameter values in the regression model. A Monte Carlo Markov Chain sampled from the posterior parameter densities over 20,000 iterations, pared down by preset burn in (2,000) and trim (5). Posterior density estimates of regression parameters at the 50% confidence interval indicate that participant pretest scores ($\beta_{z\text{PreScore}}$: [0.509, 0.618]), institutional grade point average ($\beta_{z\text{GPA}}$: [0.087, 0.205]), and the number of times they engaged in drawing activities ($\beta_{z\text{Drawing\_opps}}$: [0.063, 0.178]) were all positively associated with posttest scores. Similar results were found on a subset of posttest conceptual items that explicitly invoked submicroscopic representations: posttest scores were positively associated with pretest score ($\beta_{z\text{PreScore}}$: [0.444, 0.561]), GPA ($\beta_{z\text{GPA}}$: [0.043, 0.172]), and the number of completed drawing opportunities ($\beta_{z\text{Drawings}}$: [0.013, 0.139]).

Consistent with early studies, this study shows that sketching may not yield a large, positive impact on learning in STEM disciplines, particularly when coupled with dynamic visualizations. While we did find that students who completed a general chemistry college course using CCC materials slightly outperformed students in the comparison group on a learning outcome measure, our analysis indicates that this difference was only weakly related to completing the sketching activities themselves. Although we did not find a large benefit of sketching for improving STEM learning in the present study, we believe additional studies of sketching as a learning scaffold are needed. The optimal design of a sketching activity remains poorly understood, but at the least our work has shown that simply producing sketches while viewing a dynamic visualization can marginally improve learning outcomes.

Drawing within experimental exploration as part of core epistemological and epistemic practices in science

Russell Tytler and Vaughan Prain

This presentation explores drawing in the context of a guided inquiry approach to teaching and learning science where students engage in guided representational challenges to explore the attributes of, and make claims about, phenomena. In this approach, constructing representations in general, including drawing in particular, operates in tandem with experimental processes to productively constrain reasoned exploration and explanations of material phenomena (Prain & Tytler, 2012). We argue that the epistemological processes central to this representation construction inquiry approach mirror epistemic practices in science. This approach encourages experimenting with and integrating visual as well as more traditional text-based literacies. Our perspective follows pragmatist accounts of the situated and contextual nature of problem-solving and knowledge generation and so we describe an empirical and systematic method of inquiry that involves a collective analysis of explanatory accounts of phenomena to establish reasoned knowledge, avoiding a priori judgments. Representations actively mediate and shape reasoning such that classroom activities focus on the representational resources used to instantiate scientific concepts and practices. In traditional accounts, representations are often cast as efficient and effective ways to introduce and illustrate abstracted concepts that are conceived of as distinguishable from the representations through which they are generated and communicated. From our perspective however, representations including drawing are the reasoning tools *through which* we imagine, visualise spatial relations and model astronomical phenomena. This view is also fundamentally Vygotskian, characterising representations as the disciplinary language tools that mediate thinking and knowing (Moje, 2007).

We will present ethnographic analyses of video sequences where groups of students respond to an open task by exploration, drawing, and talking to reason about phenomena. Our aim is to investigate a) the variety of ways that drawing operates to support reasoning and learning, b) the conditions when drawing is effective in promoting quality learning. As part of the analysis we investigate counter examples where drawing does **not** substantially contribute to the learning and the features of tasks including teacher framing and support that are important to ensure drawing contributes to learning in ways consistent with epistemological opportunities and practices in scientific drawing. We report on two types of study, each involving video capture of primary students' interaction with objects in groups, to draw and otherwise represent their reasoning to problem-solve and explain:

1. classroom situations where teachers are developing the representation construction approach and students are engaged in representational challenges as part of coherent sequences in topics of astronomy, invertebrate studies, and consumer science.
2. single lessons in a specially designed learning classroom with 10 wall and ceiling mounted video cameras with zoom and tilt capacity, and radio microphones on each desk, controlled from a room with visual access. Single lessons were conducted for the topics of levers, flower classification, toys, and astronomy.

Analysis was ethnographic with group investigation, drawing and discussion selected to represent a variety of ways in which student drawing supported, or was ineffective in supporting, student reasoning and learning. First, in relation to a) the ways in which drawing contributes to reasoning and learning. 1) representing through drawing was effective in framing/constraining student attention to relevant details of phenomena, in forcing a focus for instance on details of flower structure, or of toy mechanisms and their interrelations 2) drawing acted as a self-check on student perceptions in that errors in perspective or interpretation were exposed, enabling correction 3) drawing acted as a common ground through which groups of students reached agreement about the visuo-spatial aspects of the problem requiring explanation 4) drawing exposed visuo-spatial aspects of student conceptions that were accessible to teachers and provided an opportunity for negotiation of meaning 5) drawing was effective in framing student observational and conceptual attention. Second, in relation to b) the conditions under which drawing was or was not effective, a distinction could be made as to whether drawing was used as a generative part of the reasoning process, or as an 'after the event' communication device. In tasks where students had been introduced to appropriate representational resources, drawing could be generative and creative. Where the task was conceptually difficult, without appropriate support, students could revert to ineffective abstracted verbal explanations with drawings not adding to their understanding. In cases where students were not engaged with the representational task as personally relevant, drawings could be subservient to talk and gesture, and lack explanatory detail. In general, in such cases, explanations were superficial.

The study has demonstrated the important role that drawing can play in inquiry approaches to conceptual learning in science. It revealed the ways in which students generate drawings that are more than copies of text or board productions to reason and learn. It also identified conditions needed for drawing to be effective, and the possibility of superficial and ineffective use of drawing if students are not engaged with the task and do not have appropriate representational resources and supports.

Drawing the body: Medical students understanding of internal organs

Dimitrios Panagiotopoulos, Shaaron Ainsworth, and Peter Wigmore

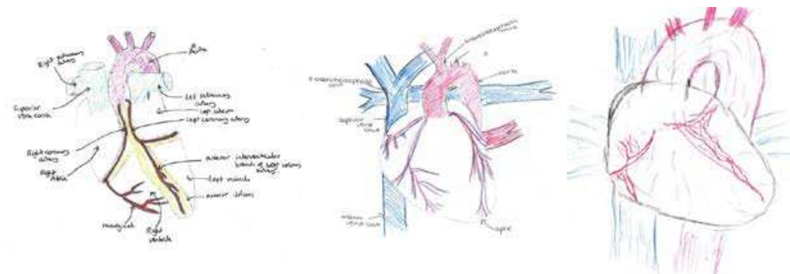
In the development of the medical practitioner, learning anatomy is considered critical. However, the value of dissection sessions is more contested with many UK medical schools removing them. Dissection classes often offer students their first hands on experience with internal structures of the human body and so those that argue for them suggest that they support students' understanding of the 3D organization of the human body (Older, 2004). Moreover, prior knowledge that students have for anatomy has been strongly influenced by the representations used in their prior education or found in popular culture. Unfortunately, in the case we will discuss, the human heart, this representation is at best partially complete and frequently profoundly incorrect. In this presentation, we focus on drawings use to assess students' understanding. The current approaches to assessment at Nottingham ask students to provide verbal descriptions after each dissection class and formal assessment is a written online multiple-choice test. This is unfortunate as students can produce or recognize appropriate verbal labels (e.g. hydrogen bonding) when their drawings revealed profound misunderstandings (e.g. Cooper et al, 2015).

At Nottingham the sequence of anatomy teaching activities repeats biweekly. Students learn about specific structures from a lecture before attending a dissection class, where following a briefing, they conduct a dissection (in small groups) lasting roughly 60 minutes. We asked 1st year medical students to draw the external features of the heart either before (N=44) or after its dissection (N=54). The heart is the second structure dissected. We also attended a clinical placement session and gave 3rd year medical students the same instructions (N=46). We developed an extensive coding rubric. To analyze specific features of the heart, the number of features were counted (total = 28) as well as whether they were correctly shaped, located and labeled. We also analyzed the shape of the heart. We coded the overall shape of the heart by diving width by height (a human heart in its natural state is about 20% wider than higher) as well as the point of maximum width (around 60% down in reality) and maximum height (around 40% to the right, so typically drawn 40% to the left in medical textbooks). Representational choices were analysed independent of content. 10% of these data were checked (all kappas above .7).

Table 1: Drawing analysis results by condition

	(1) Pre Dissection	(2)Post Dissection	(3) 3rd year	ANOVA (F,2,144)	Post hoc Comparisons
Features Present	52.6% (17.7)	45.4% (13.9)	37.8% (17.9)	9.11, $p<.001$, $p\eta^2 =.114$	1 v 2 = .096, 1 v 3 = .001, 2 v 3 = .070
Accurately located	39.3% (16.9)	34.5% (13.3)	27.5% (15.3)	6.99 , $p<.001$, $p\eta^2 =.090$	1 v 2=.352, 1 v 3=.001, 2 v 3=.068
Accurately shaped	37.7% (16.3)	32.3% (13.8)	25.8% (14.0)	7.42, $p<.001$, $p\eta^2 =.095$	1 v 2=.218, 1 v 3=.001, 2 v 3=.087
Accurately labeled	53.8% (30.3)	36.7% (31.4)	6.4% (19.4)	33.91, $p<.001$, $p\eta^2 =.325)$	1 v 2=.009, 1 v 3=.001, 2 v 3=.001
Overall Shape	101.7% (16.6)	101.1% (20.6)	107.9% (19.4)	1.83, $p=.164$, $p\eta^2 =.025$	1 v 2=1.00, 1 v 3=.386, 2 v 3=.234
Depth of Max Width	53.6% (13.5)	46.5% (17.0)	61.4% (18.5)	10.0, $p<.001$, $p\eta^2 =.124$	1 v 2=.113, 1 v 3=.082, 2 v 3=.001
Point of Max Height	56.1% (14.8)	57.2% (14.8)	46.8% (16.0)	6.65, $p=.002$, $p\eta^2 =.086$	1 v 2=1.00, 1 v 3=.013, 2 v 3=.003

Analysis of the features showed a multivariate effect of condition ($F(8,278) = 8.24$ $p<.001$, $p\eta^2 =.192$) with all four variables showing a main effect of condition. Tukey tests revealed the same pattern for all variables: i.e., that before dissection 1^{st} years draw hearts which were richer in accurately labeled shaped and located content compared to 3rd years with 1^{st} year post dissection being somewhere in the middle. Analysis of the overall shape of the heart showed a multivariate effect of condition (F(6,280), = 3.86 p=.001, $p\eta^2$ =.076). Although there was not a significant improvement in students' drawings of the overall shape, the specifics of this shape did improve with students in third year showing shapes which placed the points of maximum width further down (which is more accurate) as well as the point of maximum height being further to the right, which also is more accurate (all Table 1). Finally, three chi squared analysis considered the representational choices of students. Here there was less of an effect as there was no difference in how they used color $\chi2$ (4, N = 144) = 1.69, p = ns) or drew in 3d (4(n = 144) = 1.74, p = ns), however third year drawings were on average more "sketch" like and were judged therefore as less clear $\chi2$ (4, N=144)=11.03, p=.026).



Pre dissection Post dissection Third Year

Figure 2. Three typical hearts from the different conditions.

Our predictions were only somewhat supported. Third years did show greater understanding of the way the heart is shaped but at the expense of remembering specific features. Moreover, students were no more accurate in their drawings of heart after dissection and in fact they were typically slightly or significantly worse depending on the measure. We suggest that dissection for these students (an undeniably affectively demanding part of medical training, especially at the beginning) did destabilize students' reliance of the prior "textbook" knowledge of the heart but did not quickly replace it with something more accurate. This study therefore does not unambiguously reveal whether dissection is helpful or unhelpful; longitudinal studies would be needed. We suggest that this research shows that drawing as a mode of assessment in anatomy is of mixed value. It is very helpful for assessing students' understanding of the spatial aspects of internal anatomy, especially shape. However, assessing specific content is time consuming and we feel adds little beyond that which could be more swiftly assessed from written texts. Currently, we are conducting grounded interviews with anatomy lecturers where their evaluation of these drawings will be compared to our assessments.

Drawings to create models of evolutionary biology

Wouter van Joolingen, Dewi Heijnes and Frank Leenaars

In computer modeling, students create models of scientific phenomena. Many modeling systems require skills in either programming or equation writing (Louca & Zacharia, 2011) making modeling less accessible to younger students. We have tried to overcome this drawback by using drawings as a basis for the creation of computational models, and so enhancing \ scientific reasoning in young students. Using a drawing-based modeling tool, students created models of evolutionary biology. The modeling task is loosely based on natural selection of the snail species *Cepaea nemoralis.* These snails have a shell color that matches the background color of the area where they live, which is explained by them being hunted by birds: snails that are camouflaged are more likely to avoid predation and pass on their genes. Students involved in the current study used SimSketch (Bollen & van Joolingen, 2013) to create their model from a drawing. Elements in the drawing are assigned with user-defined *behaviors*, which are represented as "stickers". In this case, students draw snails, birds and areas where snails can live. Snails are assigned moving and reproductive behavior, with a probability of mutation of color on each reproduction. Birds receive a behavior to predate on the snails. The areas serve as background and the probability of being eaten depends on the color difference between snail and background.

Students from grade 7 and 9 worked on the assignment during one class period of fifty minutes. 15 minutes were spent on introducing the context and explaining the workings of SimSketch, 30 on modeling and 5 on discussing what students thought of the experience. Students' scientific reasoning was analyzed to determine what elements in the assignment and modeling tool have an influence on scientific reasoning. We used three iterations of data collection, each with a modified version of SimSketch, based on the results from the previous iteration. Their conversations were analyzed using part of the method for assessing reasoning complexity used by Hogan, Nastasi, and Pressley (1999). Reasoning complexity is used to gauge the quality of students' learning, which focuses on their ability to explain and elaborate on their understanding, rather than on comparing their knowledge to that of experts. For each iteration, the main results are described Table 2.

Table 2. Overview of the main results of the three iterations in the study.

No.	Students	SimSketch Features and assignments	Main findings	Reasoning
1	4, grade 7	Basic version, three areas for snails	Reasons outside the model are used	Generally low
2	6, grade 7	+ Hunting behavior modifiable by the learner.	More reasoning within the model, less outside causes.	More complex reasoning
3	2x6, grade 9	+ 2 instructions 1) focusing on research questions, 2) on the modeling tool itself Statistics tool added.	Students with instructions about the modeling tool act more playfully.	More complex reasoning when instructions focused on the modeling tool

A key finding from these iteration is that details in the design of the modeling tool can have substantial influence on the reasoning behavior of children. For instance, in the first run, children expressed reasoning that involved "magic" arguments from outside the model:

> T: What is, you think, the influence of the colors of the areas on the snail shells- on the colors of the snails? S: They become… darker?
>
> T: How so? S: Because the green color influences it or something, or it makes them have darker children.
>
> T: Why would that make them have darker children? S: Because they take up a bit of the pigments or something?
>
> T: From the leaves? S: Could be.

However, in the second study in which students now explicitly modified the hunting behavior of the birds typical reasoning:

> T: How does it choose which snail it hunts? S: On the one that is closest- random.
>
> T: Why at random? S: They can also go at the prettiest. But now- If they just pick the one that is closest. That is the most logical, really. That they hunt the one that, that they are like 'oh see there is the snail I'll take that one'. You know, they are not going to fly ten kilometers to get him if they have already seen fifty.

The third iteration of study contrasted two groups to explore how best to prepare students to model to learn. In the first group, emphasis was placed on the research question as students were asked early on what they thought was going to happen with the colors of the snails and the explaining the workings of SimSketch was put in second place, whereas, for the second group emphasis was placed on explaining SimSketch. Students in this second group spoke more about the modeling process in reasoning terms than the first group (a total of 87 utterances versus a total of 36). As expected, students who worked on the modeling task with SimSketch were generally able to create a model of evolutionary processes and reason about this model. This is a solid foundation to build from and to consider improvements to the tool design and the nature of instructions to enhance students' reasoning. We conclude that as students display more appropriate reasoning when they are able to modify the bird's behavior this indicates there is probably a minimum level of control needed in the modeling processes. By constructing the cause for the hunting behavior themselves, students were encouraged to include that in their reasoning about evolution. The result of the third study indicates that keeping the modeling task open, by not focusing too much on the research question, actually engaged students in deeper and more complex reasoning about the domain. This seems in contrast with earlier studies in which the modeling tasks were heavily scaffolded (Mulder, Lazonder, & de Jong, 2014). Their models improved with more scaffolding. However, in that study students' reasoning processes were not studied. The current study is an indication that too much scaffolding and automation of modeling processes may get in the way of learning from the models and modeling processes. This informs the design of drawing-based modeling tools, lessons and further study.

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