Designing Drawing Activities to Support Simulation-based Learning in Quantum Mechanics

Shaaron Ainsworth, University of Nottingham, Shaaron.Ainsworth@nottingham.ac.uk
Antje Kohnle, University of St Andrews, ak81@st-andrews.ac.uk
Gina Passante, California State University Fullerton, gpassante@fullerton.edu

Abstract: In recent years, the argument that drawing can play a fundamental role in learning in the STEM disciplines has received much support. One area that is receiving growing attention is whether drawing is of value when students work with multi-representational simulations. In this paper, we report on a design based research (DBR) project to teach intermediate-level undergraduate quantum mechanics (QM) through drawing and simulations. We articulate six distinct pedagogical roles of drawing, principles for task design and success criteria for drawing both prior to and whilst working with the simulations. This approach has been iteratively improved through three annual cycles of implementation in two universities in two different countries. Our findings illustrate a variety of theory-informed reasons to draw to learn in science and consider what scaffolding is required to help students make best use of such an approach.

Introduction

Recently, a number of articles have argued that students should be encouraged to draw (e.g. Fiorella and Zhang, 2018; Wu and Rau, 2019). The majority of this research has asked students to read written text and then externalize their understanding in a drawing. In this paper, we describe part of our DBR project which uses drawing to support learning from simulations, a limited but growing area (e.g. Stieff et al, 2018; Wu and Rau, 2018; Zhang and Linn, 2011); defining drawing as the purposeful construction of a visual representation such as graphs, pictures and diagrams. The context for our work is intermediate-level undergraduate QM at two different institutions in the UK and the United States. These courses cover standard wave mechanics and intrinsic angular momentum as well as relevant mathematical approximation techniques. They focus on mathematical formalism and the development of conceptual and visual understanding of the theory. Kozma and Russell (2005) argued that a key component of professional science practice is representational competence: i.e. how representations work, how they relate to one another, how to choose appropriate ones and how to reason with them. Unfortunately, research shows that this is very demanding for students to acquire. One solution to this problem is multi-representational simulations that employ a variety of linked representations of phenomena to allow students to change parameters and observe their impact. Consequently, students have the opportunity to develop their representational competence, especially that pertaining to understanding the multiple representations shown and how they relate to each other and the depicted phenomena (Rutten, van Joolingen and van der Veen, 2012). However, simulations are not automatically effective. Students can struggle to understand the representations, may not be able to relate them and, in general, need support. A second concern is that often students do not get to create the representations they observe in the simulation, their activities (mostly) being limited to changing parameters and interpreting results. We thus developed drawing activities alongside simulations that are intended to develop representational competence in QM. In this paper, we illustrate the variety of pedagogical roles that drawing can serve to achieve this. Moreover, it becomes clear that drawing activities need to be designed differently depending upon their specific role and similarly instructors need to assess the success of these drawing activities differently. We suggest that the significance of this research is that it allows us to develop "humble theory": i.e. one that improves learning by generating practical design principles for a particular set of concepts and contexts by addressing how drawing and simulations can support the visual learning of QM.

The roles of drawing in learning with simulations in quantum mechanics

In existing research, learners have been asked to draw when they are preparing to learn with the simulations, during their interactions with them and afterwards as they reflect (e.g. Stieff et al, 2018; Wu and Rau, 2018; Zhang and Linn, 2011). Although sometimes these studies have asked "when is it most effective to draw?" our starting point is that the answer to this question is "all of the time". Instead our key questions are what roles can drawing play in these phases for learning QM and how tasks should be designed to fulfil this, and thus our task design act as the humble theory principles. QM is challenging in part due to its often counterintuitive phenomena far-removed from everyday experience, and the complicated mathematics required to solve even simple phenomena. Students on these courses can often perform required calculations, but do not always manage to interpret them. Accordingly, we have developed a number of multi-representational simulations embedded into scaffolded worksheets (called simulation-tutorials). These are intended to allow students to become proficient in the use of diagrams and graphs as well as mathematical formalism so they could apply multiple approaches to problems and check for consistency in their answers across these forms. Unfortunately, visual representations in QM are themselves not easy to understand, due to their depiction of abstract and complicated quantities that are often multi-dimensional and vary with time, the inherent uncertainty often associated with quantum properties, and the potential confusion with similar depictions in classical physics. Consequently, our activities are designed as a sequence which moves from establishing that students can understand the basic properties of these representations and the relations between them, to ultimately being able to reason qualitatively through them. The simulation-tutorial activities include drawing alongside other tasks (critiquing a representation, writing a formula, gesturing to add time to static forms) in two distinct phases. In the first phase students complete tasks prior to working with the simulation in the second phase. At this time, we have not yet implemented reflective tasks after the simulation, but future iterations will include these and so we return to outline ideas for these in the discussion.

To assess if the designed tasks have fulfilled their role, we also need to code the students' drawings. Much research on assessing drawing to learn takes a content approach, scoring drawings in terms of their domain accuracy or inaccuracy to identify misconceptions. Alternatively, drawings can be coded in representational terms: such as into types of representations or the fidelity to the form. Finally, approaches such as diSessa (2004) focus on meta-representational competence, for example asking if a representation is complete, parsimonious, or systematic. Again, we do not seek to find the single best way to code a drawing; instead matching our success criteria to the role that the drawing activity is intended to play, and so utilising all these approaches as appropriate.

We have now implemented activities at the University of St Andrews (StA) and California State University (CSUF) in three annual cycles assessing drawings to iterate and improve upon activity design. Over 200 students have participated with class sizes varying between 20 (CSUF) and 100 (StA). At both institutions, students begin the activities in a class working collaboratively and finish activities independently for homework.

Drawing to learn prior to and with multi-representational simulations

We suggest that students will be able to work productively with the multi-representational simulation if they utilise their relevant prior knowledge of the phenomena, if they know how to interpret, construct and translate between some of the simpler representations and if they are prepared to understand and appreciate the value of new representations. We thus designed drawing activities for these roles. Table 1 presents the pedagogical role, the design principles, provides examples abstracted from our materials, and articulates the drawing coding criteria we used to determine if the activity fulfilled its intended role. Note representation is rep in the table for brevity.

Table 1: Roles of drawing *prior to* learning with the multi-representational simulation

Role	Design Principles	General Description	An example	Success criteria
Activate prior knowledge	Should be easily within reach and relevant for the learning task.	Draw familiar relevant visual reps.	Draw a familiar graph.	Correct in terms of domain accuracy and rep format.
Practice relating reps	Make relating reps achievable by transforming from a more familiar/simpler to unfamiliar/ more complicated rep. The less similar the reps, the more scaffolding is needed.	Construct a second rep on the basis of an existing one; within or across modes.	Transform a given mathematical expression into a visual rep.	Completeness – whether all information has been included in the transformed rep.
Invent a rep	Invention requires meta-rep competence & domain knowledge. The task should generate multiple solutions. The simulation will later offer expert solutions so that students can compare their approaches to this. Scaffolding develops visual repertoire by encouraging extension from familiar reps.	Invent a visual rep that they have not previously seen.	Create a 3d depiction of a function which had only been encountered as 1d and 2d depictions.	Reps should follow principles and practices of scientific reps in general and QM in particular. They should encapsulate key components of the phenomena. Canonical solutions are not required.

We asked students to construct a known representation at the beginning of the activity, as there is abundant evidence that learning is supported if students activate relevant prior knowledge at the beginning of a learning sequence. Moreover, it has been argued that constructing a visual representation is particularly successful as it results in an external, inspectable, realisation of this knowledge (Wetzels et al, 2010). A second drawing activity focused on helping students relate representations, as there is abundant evidence that this is both a vital component of representational competence as well as something students need much practice to develop (e.g. Kozma and Russell, 2005). Whilst dyna-linking in the simulations is something that is often recommended for this purpose (and indeed is also implemented in ours), asking students to construct a second representation on the basis of a first before learning with the simulation was intended to encourage deeper processing of the relationship between representations, as students can unfortunately avoid doing so when the representations are dyna-linked in the simulation. The final activity prior to working with the simulation was to invent a visual representation by thinking about the phenomenon and trying to encapsulate its key components. This activity is aligned to the Inventing to Prepare for Future Learning approach of Schwartz and Martin (2004), as we did not ask students simply to recall an example from their textbook but instead asked them to create something new by redesigning, combining and extending from more familiar representations. This invention activity draws upon students' representational and meta-representational competence as well as their understanding of QM. It does not need to lead to canonical representations but instead prepares students to learn from the simulation.

Whilst learning with the simulation, we suggest that students are able to learn productively if they attend to the presented representations, understand their properties and ultimately if they can reason in increasingly expert ways with the representations they encounter (Table 2). As literature is replete with examples of students insufficiently processing presented representations, we asked them to copy a representation to focus their attention on details and subtle properties they might otherwise miss and to help overcome shallowing processing (Wiley, 2019). We then asked students to go beyond a representation they were presented with and extend their understanding of its format or operators by constructing a new representation which includes features not depicted in the simulation (Kozma and Russell, 2005). The final activity then presents students with fictitious dialogue which confronts common incorrect ideas. This technique can focus on concepts, on representations, and/or on procedure. Our example asks students to draw representations to work out which claim is correct and then correct the mistaken statement ensuring students need to align their verbal reasoning with the drawn graph.

Table 2: Roles of drawing *whilst* learning with the multi-representational simulation

Role	Design Principles	General Description	An example	Success criteria
Close observation	The rep is central to the domain and copying it should be easily achievable; could be familiar or unfamiliar reps. Scaffolding focuses attention on aspects that might be overlooked	Draw a rep presented on screen.	Draw the graphs and diagram as seen in the simulation for a particular configuration.	Accuracy in terms of domain and rep format.
Understand the format and operators of a rep	The rep should be central to the domain and required later. The answer should not simply be observable in the simulation but can be derived from it and then applied.	Draw something similar to a previously seen rep but which extends the format/operator to a new example.	Combine two graphs not shown in the simulation using the same approach as illustrated in the simulation for other cases.	Accuracy in domain and rep features, especially those pertaining to the new properties.
Reason with reps	The task should reflect authentic (albeit often simplified) scientific reasoning. The constructed rep should be core to the solution/argument.	Students reason with reps. to solve problems, justify claims or assess the truth of an assertion.	Here are two alternative claims. Draw a graph to determine which is right and correct the others' mistake.	Domain accuracy; attending consistently to appropriate features of the rep to reason.

Conclusion

Over time, we have refined our emerging design principles and task design by analysing the representations constructed by the students using the success criteria outlined in the tables. All authors worked to develop the coding approach outlined in the final column of the tables, and the two physicist co-authors independently evaluated all drawings against these criteria (always achieving high reliability). We have found that our emerging design principles and their instantiation in activities mostly worked as intended. For example, drawing to activate prior knowledge and to observe the presented representations resulted in ca. 90% of drawings being judged as meeting the success criteria by the third cycle. Activities intended to elicit invention and variation did so, as we coded seven different types of response to the invention task, including those that redesigned previous drawings, those that combined previous drawings and those that combined and extended them. However, to achieve this success we have had to refine our task design in three main ways. The first has been to make difficult tasks more achievable by including more explicit prompts. For example, relating representations was initially difficult for students and we amended the activities over the three cycles to include more visual cues to the form of the required graphs. Secondly, some tasks did not generate complete responses from students and still need to be further developed to do so, in particular those that ask students to translate from a visual representation into words, where only 20% of students in the third cycle did so fully for one of the activities. Thirdly, we needed to be alert to sequencing, ensuring that earlier activities scaffolded the later ones. For example, we included additional activities relating familiar and unfamiliar 1d and 2d depictions prior to the 3d invention task to help students invent representations.

As a DBR study without a control group, we cannot claim that such an approach has led to increased outcomes relative to previous practice where simulation-tutorials did not include drawing activities. However, our observations of student engagement and their overall success in drawing and reasoning means that we intend to continue with these activities. Moreover, future iterations could increase the roles of drawing. The main opportunity is to use drawing after learning with the simulation. For example, Wu and Rau (2018) prompted students to amend an earlier created drawing after they had learned with the simulation. Another activity could be to ask students after a period of delay to draw representations they had observed in the simulation as a form of retrieval practice. We also do not propose the activities we have designed here are a complete set of all drawing activities that could be beneficial in earlier phases. For example, asking students to predict by drawing the results they would see when they ran the simulation with different values seems likely to be a fruitful way to implement a predict, test, and explain cycle (especially if they amended, as necessary, drawings subsequently). We hope that illustrating many ways that drawing was used to support learning with multi-representational simulations leads to future research that need not focus on asking IF drawing is effective but instead can identify and refine the design principles, activities and success criteria of drawing to learn in this way.

References

diSessa, A. A. (2004). Metarepresentation: Native competence and targets for instruction. *Cognition and Instruction, 22*(3), 293-331.

Fiorella, L., & Zhang, Q. (2018). Drawing boundary conditions for learning by drawing. *Educational Psychology Review, 30*(3), 1115-1137.

Kozma, R., & Russell, J. (2005). Students becoming chemists: Developing representational competence. In J. K. Gilbert (Ed.), *Visualization in Science and Education* (pp. 121-146). Dordrecht: Kluwer.

Rutten, N., van Joolingen, W. R., & van der Veen, J. T. (2012). The learning effects of computer simulations in science education. *Computers & Education, 58*(1), 136-153.

Schwartz, D. L., & Martin, T. (2004). Inventing to prepare for future learning: The hidden efficiency of encouraging original student production in statistics instruction. *Cognition & Instruction, 22*, 129-184.

Stieff, M., Scheiter, K., Ainsworth, S., Bohrmann-Linde, C., & Schall, M. (2018). Drawing for Learning from Dynamic Visualizations in Science. International Society of the Learning Sciences, Inc.[ISLS]

Wetzels, S. A., Kester, L., & van Merriënboer, J. J. (2010). Use of external representations in science. *Use of Representations in Reasoning and Problem Solving: Analysis and Improvement*, 225-241.

Wiley, J. (2019). Picture this! Effects of photographs, diagrams, animations, and sketching on learning and beliefs about learning from a geoscience text. *Applied Cognitive Psychology, 33(1)*, 9-19.

Wu, S. P. W., & Rau, M. A. (2018). Effectiveness and efficiency of adding drawing prompts to an interactive educational technology when learning with visual representations. *Learning and Instruction, 55*, 93-104.

Wu, S. P. W., & Rau, M. A. (2019). How students learn content in science, technology, engineering, and mathematics (STEM) through drawing activities. *Educational Psychology Review, 31(1),* 87-120.

Zhang, Z. H., & Linn, M. C. (2011). Can generating representations enhance learning with dynamic visualizations? *Journal of Research in Science Teaching, 48*(10), 1177-1198

