Learning about Dynamic Systems by Drawing

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Abstract: The act of drawing as a means of publicly presenting one's ideas is not *cognitively neutral*. Drawing, perhaps in a way that is somewhat like self-explanation, influences knowing and learning. It can help learners evaluate and transform their understanding, help them communicate their ideas, and be a motivating and highly engaging way to process and express scientific concepts. Asking learners to draw when they are exploring dynamic systems can be highly beneficial. Yet analyses of drawings may depend on learners' accompanying speech and gestures. Learners also benefit from pedagogical and technological support in making drawings that support modeling. This symposium draws together research on how people use drawings when learning about dynamic systems. It explores different theoretical frameworks for analyzing drawings, their impact, interactions with prior knowledge, and the different roles drawing can play in learning and asks how learning by drawing can be enhanced.

Introduction

Asking learners to draw when they are exploring complex ideas is not cognitive neutral. In fact, previous work (e.g. Gobert & Clement, 1999; Kress, Jewitt, Ogborn, & Tsatsarelis, 2001; Prangsma, Van Boxtel, & Kanselaar, 2008; Van Meter & Garner, 2005) as well as some of the papers presented in this symposium suggest the act of drawing can be highly beneficial. Yet, compared to our knowledge of how people learn by interpreting text (reading) and pictures (viewing), or by constructing text (writing) or speech (verbal reporting) we know relatively little about how drawing affects learning. Consequently, the focus of this symposium aims to redress this balance a little by increasing our understanding of how knowledge and learning about dynamic systems is influenced by drawing.

Dynamics systems such as the workings of the circulatory system, the process of chemical reactions or the thermodynamics of the earth are an ideal arena in which to explore how drawing shapes learning. Such topics are complex for students to understand and there is much evidence to suggest that learners need support to develop deep knowledge of these systems. Researchers have therefore explored how different forms of representation can help learners develop this knowledge. Rather than a simple textual presentation, learners have been provided with pictures, animations, interactive simulations and even augmented reality environments to help them understand dynamic systems (e.g. de Jong & Ban Joolingen, 1999; Hegarty, Kriz & Cate, 2003; Ohlson, Moher & Johnson, 2002). In contrast, in this symposium we have focused not on the representations that are provided for the learner but on the graphical representations that learners construct for themselves.

The paper by Zhang and Linn addresses how learners can be helped to understand the processes involved in chemical reactions by interacting with a dynamic visualization of atomic interactions in hydrogen combustion. Subsequently, learners either drew four intermediates phases of hydrogen combustion or selected four appropriate pictures. Whilst both techniques supported learning, the relative effectiveness of the strategies was dependent on student's prior understanding. Zhang and Linn suggest that drawing helped learners to distinguish their ideas about chemical reactions, helping those with low knowledge realize this lack and prompt them to overcome it whereas selecting existing pictures prompts students with some higher knowledge of develop and extend their ideas.

Ainsworth explores how learners can be helped to draw more effectively. She reports on a series of small experiments whereby students learn about the structure and the functions of the cardio-vascular system by drawing after reading texts. Two different approaches have been trialed: a) encouraging constructive processing of the text by self-explanation prior to drawing; and b) altering the audience and function of the intended drawing by asking learners to draw for themselves, a peer or draw a self-explanation.. Analysis of these studies is on-going but so far shows that these approaches alter the drawings that students make and this may further impact on learning.

Nathan & Johnson also ask learners to draw the human circulatory system. However, the focus of their work is on exploring the limits of drawing as a mode of expression, especially when learners need to convey a dynamic, three dimensional process in a static two dimensional form. They show that our understanding of learners' drawings in enhanced if we treat them as instances in a multimodal system and that the gestures and speech that accompany a drawing are a crucial part of this system.

The last paper in the symposium is by Van Joolingen and colleagues. They focus on learning dynamic systems through modelling. Drawing is shown to be valuable in two ways. Firstly, it can help learners prepare for the modelling task by requiring them to be explicit about the variables in their model activating prior knowledge and acting as a constraint on the solution. Secondly, a drawing, if constructed using specific formalisms, can act as the model without further transformation.

The papers in this symposium were selected to address a number of major issues in the area of drawing to learn. The first issue explored is the varied roles drawing plays in learning. Across the papers, we see drawing used as preparation for learning new ideas, during reading about new concepts, as a way of reflecting on presented material, and for communication and assessment. Secondly, the researchers highlight the cognitive processes that drawing supports. Properties of drawing as a medium itself as well as the socially compelling drive to be understood by other interlocutors shape the process and outcomes of drawing. Taken together, the papers suggest that drawing helps learners make their ideas explicit, perhaps in a way that is analogous to self-explanation, so that they are able to overcome gaps in the material or generate new inferences. A third important unifying theme is the way that the papers do not treat drawing as a 'black box'. Rather than asking "Does drawing support learning?" they explore questions such as "What ideas are conveyed by a drawing?" and "How does drawing support learning?" by analysing the characteristics of learners who benefit from learning, how the nature of the representations reveal learners' conceptualization of the domain, how learners' transform their understanding across modes of representation, whether that transformation predicts learning, and how drawings can be understood as part of a multi-modal construction.

There are, however, important differences between the approaches described in the papers. Drawing has been conducted either free hand with pen and papers or with computer-based tools. It has been done solely for the purposes of a learners' own understanding, to communicate with other people, or to provide input for a computer model. Implicitly, there are differences in the theoretical frameworks the authors use to situate their work that should contribute to a lively interaction among presenters and members of the audience. These common threads and divergent points of view will inform the discussion offered by Peggy van Meter.

Interest in research on the nature of drawing and evidence of learning by drawing is growing in the Learning Sciences. This symposium offers a timely opportunity to reflect upon a research agenda for learning by drawing. By contrasting these four diverse perspectives we can explore which theoretical approaches/models should inform our understanding of learning by drawing, such as characteristics of learners, tasks and the social and technological environments within which drawings are constructed and explained. We can also gain purchase about broad concerns about how to analyze drawings, as well as questions such as how drawing shapes and is in turn shaped by cognitive structures that mediate drawing to learn and communicate. As a consequence we will be in a better position to understand how we should support learners as they draw to learn, and researches interested in analyzing data from drawing tasks.

How can selection and drawing support learning from dynamic visualizations?

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When students generate drawings it helps them learn from expository text (Van Meter & Garner, 2005) and from scientific visualizations (Zhang & Linn, 2008). Generating a drawing requires students to select information, to distinguish this information from their existing views, and to represent connections among the selected elements. Dynamic visualizations support chemistry learning because they illustrate interactions at the molecular level (Ardac & Akaygun, 2004; Kozma, 2003; Williamson & Abraham, 1995). Yet students often find them difficult to follow and neglect nuanced information such as bond breaking and formation. Learners need guidance to help integrate ideas about molecular interactions and link with observable and symbolic ideas. Our previous study demonstrated that students who generated drawings when using dynamic visualizations can integrate more ideas than those who learned only with visualizations. To further clarify the mechanism of drawing, this study compares selection among drawings and generating drawings to help students learn chemistry with dynamic visualizations.

Students studied chemical reactions using the WISE (Web-Based Inquiry Science Environment) *Hydrogen Fuel Cell Cars* project designed following the Knowledge Integration framework (Linn & Hsi, 2000). Students interact with a dynamic visualization showing atomic interactions during hydrogen combustion (see Figure 1) for a screenshot of the visualizations) and integrate symbolic, molecular, and observable ideas to understand hydrogen fuel cell cars. Drawing and selection occur after the visualization step. The drawing activity requires students to generate four pictures to represent intermediate phases of hydrogen combustion using the WISE drawing tool. In selection, students select four drawings among twelve to model the reaction processes. We hypothesized that drawing helps students learn from the visualization because it encourages them to distinguish among ideas and enables them to realize flaws in their previous interpretations. The selection activity also requires distinguishing among ideas.

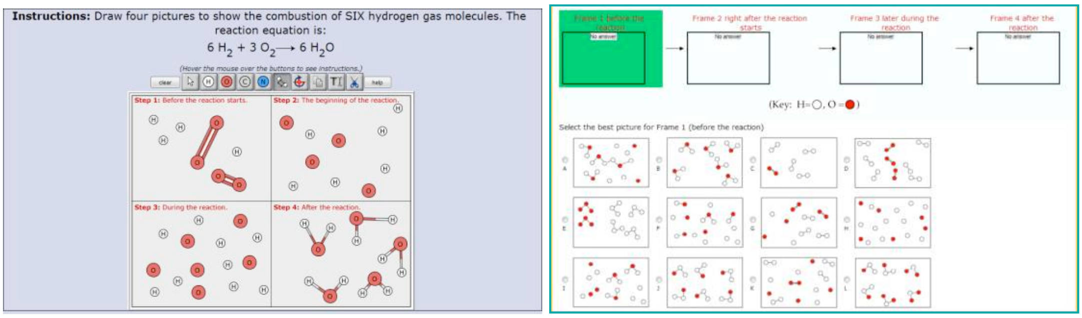


Figure 1 Left: a screenshot of the online drawing tool. Students create four pictures to represent four intermediate phases during hydrogen combustion; Right: a screenshot of the selection activity. Students select four pictures from twelve to represent four intermediate phases during hydrogen combustion.

Eighth graders (N=172, six classes) in a public middle school were assigned to either drawing (n=83) or selection (n=89) conditions. Students in both conditions spent 40 minutes interacting with the visualization and working on the drawing or selection tasks as part of the week-long project. Comparing student performance on the posttest with pretest as covariate shows that both groups gained understanding [$t(171)=21.45$, $p<.0001$, effect size=1.64] and performed equally well [$F\ (1,\ 169)=1.72$, $p=.19$]. This suggests that both drawing and selection support student learning.

Using pretest drawing performance, we grouped students based on knowledge integration rubrics (Figure 2). We found that selection and drawing have similar impact on students with high [$t(16)=.36$, $p=.73$] and low [$t(80)=.78$, $p=.44$] levels of integrated ideas before the project. For students with partially integrated ideas (medium level), drawing is less effective than selection [$t(71)=2.25$, $p<.05$].

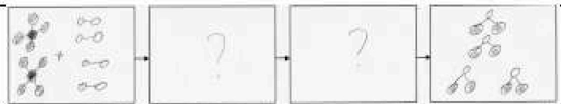
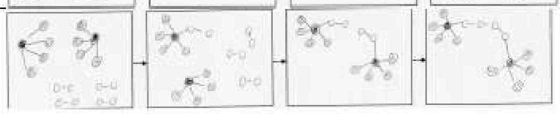
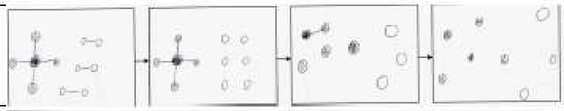
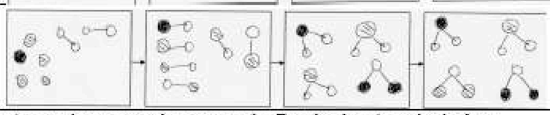
KI Levels	Student ideas	Descriptions	Student sample answers
Low	No/Wrong ideas	Incorrect ideas about reactants & products, no idea about the reaction process.	Leave all boxes blank, or draw reactants and products incorrectly
	Instantaneous view	Represent reactants and products correctly, but no ideas about the reaction process.	
Medium	Big Molecular view	Have the idea of bond formation but explain the reaction as all molecules and atoms forming into one big molecule as the end products.	
	Breaking view	Have the idea of bond breaking but represent the reaction as all molecules try to break bonds and the end products are separated atoms moving freely.	
	Exchanging view	Have the idea of molecular rearrangement but represent the process as exchanging atoms between molecules.	
High	No conserve	Have the ideas of bond breaking and formation, and represent them correctly. But the drawings don't show conservation of matter.	
	Correct	Correctly represent bond breaking and formation using molecular representations. All drawings follow the conservation of matter law.	

Figure 2. Categorization of students' ideas about chemical reaction processes on the pretest. The sample answers are collected from students' answers to a question asking to draw 4 pictures to represent how methane combustion occurs at the molecular level.

Overall this study reveals that it is crucial to encourage students to distinguish among ideas when learning with visualizations. Drawing prompts learners to distinguish among ideas currently in their repertoire. For students who started with incorrect or no ideas about chemical reactions, drawing enables them to realize the insufficiency of their previous understanding and prompts them to revisit the visualization for new ideas. For students who had some correct ideas, selection requires them to analyze new ideas represented in the choices and distinguish among their own ideas and new views. Compared to drawing, selection may add ideas and enable students to develop criteria for distinguishing ideas.

Improving learning by drawing

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Drawing to learn can be a very successful way to help learners engage with complex concepts. For example, it can help people observe, plan writing, improve memory, reduce anxiety, increase motivation, *etc* (Van Meter & Garner, 2005). However, Leutner, Leopold & Sumfleth (2009) found that drawing after reading significantly decreased performance. Moreover, research shows that learners benefit from support during drawing. The form this support has taken includes task instruction to focus on specific aspects of the task (Alesandrini, 1981), providing pre-existing materials such as scenes and cut-outs (Lesgold, Levin, Shimron, & Guttman, 1975) or complete drawings for learners to compare with their own (Van Meter, 2001). This often leads to improved outcomes. For example, Van Meter, Aleksic, Schwartz, & Garner, (2006) compared children learning from a science text when they either read an illustrated text, read then drew, read, drew and then saw illustrations or finally read, drew and saw illustration combined with prompts to compare to their own drawings. Sixth grade children how received support in the drawing process outperformed students in the other conditions on tests of problem solving knowledge. However, studies such as these are unclear as to the extent to which the benefits come from active interpretation of multiple representations (itself often associated with improved learning, . Ainsworth, 2006). Consequently, this paper summarises studies which have explored whether learning by drawing from written text which describe the structure and function of the cardio-vascular system can be improved without providing additional pictures. Two different approaches have been trialed: a) encouraging active processing of the text prior to drawing; and b) altering the audience of the intended drawing.

There are many ways to improve text comprehension but one strategy that has been found to be particularly effective is that of self-explanation (e.g. Chi, 2000). When learners self explain, they go beyond the information in the written text to generate inferences that help them construct new knowledge. Self explanation thus helps learners to overcome gaps in the presented material or helps them build more accurate and complete mental models. A drawing of self-explained text may then reflect this new knowledge in an external and consequently inspectable visualisation, leveraging graphical representations known benefits of computational offloading (e.g. Scaife & Rogers, 1996) which could in turn prompt new self-explanations (e.g. Ainsworth & Loizou, 2003). Additionally, drawings due to their specificity and perceptual advantages may provide learners with complementary insights to those provide by the self-explanation process. Examples from a pilot study are shown below which suggest that self-explanation may indeed support drawing as those constructed after self-explanation are typically and contain more transformations of the original text.

a b c D

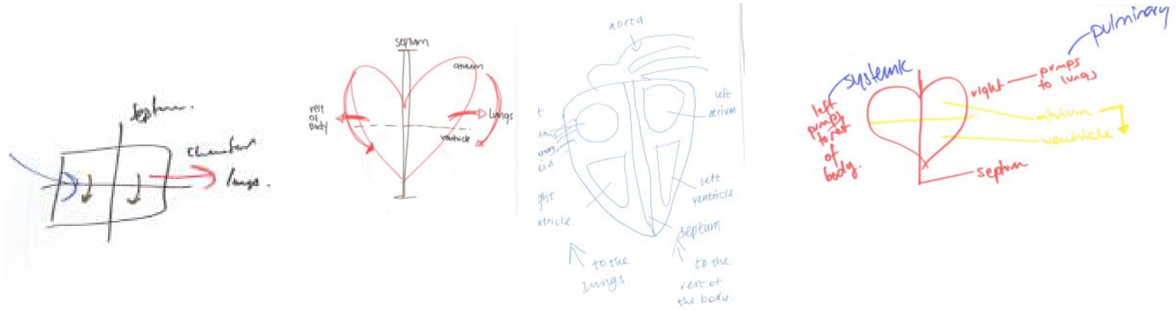

Figure 3. Drawings created by 4 participants a & b) drawing and c & d) SE + drawing conditions after reading "*The septum divides the heart lengthwise into two sides. The right side pumps blood to the lungs, and the left side pumps blood to other part of the body. Each side of the heart is divided into an upper and a lower chamber. Each lower chamber is called a ventricle. Each upper chamber is called an atrium. In each side of the heart blood flows from the atrium to the ventricle*"

The second series of studies have taken their inspiration from researchers who have studied writing as they have long recognised that the social context of the writing (including a writer's collaborators and their intended audience) will shape the process and outcomes of writing (Flower & Hayes, 1981). However, in the context of drawing this has received relatively little attention to date (although see Schwartz (1995) for an exception whereby drawers who worked in dyads created more abstract visualisations than those who worked alone). My research has asked learners to draw an explanation for themselves, for a peer or has asked them to draw a 'self explanation' for themselves (a self-explanation diagram follows a similar protocol to a verbal self-explanation in that it asks learners to go beyond the text to generate new inferences).

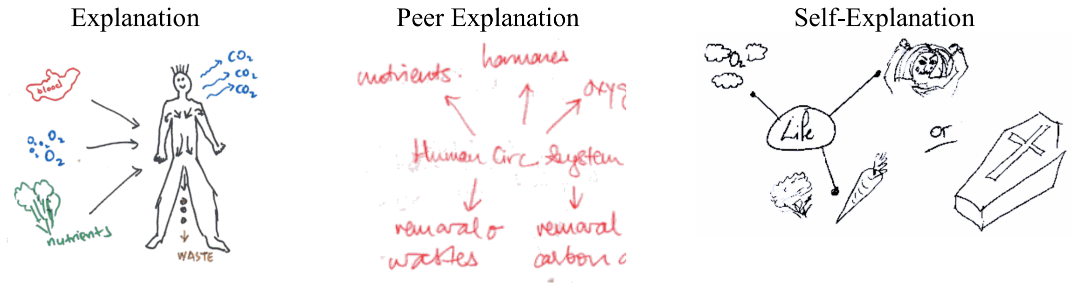

Figure 4. *Shows three drawings created after students read "Human life depends on the distribution of oxygen, hormones and nutrients to the cells in all parts of the body & the removal of carbon dioxide and other waste".*

Analysis of the pilot studies suggest that all three forms of instruction help students learn (although as they were conducted with slightly different materials and tests no direct comparisons can be made as to their relative effectiveness). It also suggests that distinctly different drawings emerge in the three different conditions. Explanations created for peers (rather than for oneself) tend to be judged as clearer and contain both more content and more words. Explanations created as 'self explanations' whilst not necessarily representing more content, do include more inferences and even indications of monitoring (ticks and question marks added to the diagram. Typically, learners who create self-explanation diagrams first directly translate the text content to the diagram and then either annotate or amend the diagram to contain these inferences.

These preliminary studies suggest that learning by drawing can be supported by strategies that encourage learners to actively process the material and then reflect their new understanding in the drawing. Current research is now extending these studies by gathering systematic evidence on the relation between different forms of support for drawing, the process of drawing and learning outcomes.

Drawing Inferences about Students' Mental Models of Dynamic Processes Depicted in Scientific Drawings: The Role of Gestures and Speech

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Drawings are commonly used in the assessment (e.g., Magnusson, Krajcik & Borko, 1999) or spontaneous articulation of scientific knowledge (e.g., Kinfield, 1993). As an activity, drawing has been shown to enhance some forms of learning and comprehension (Ainsworth et al., 2007; Gobert & Clement, 1999; Van Meter & Garner, 2005; Zhang & Linn, 2008). Yet learners regularly bump up against inherent constraints of the static, two-dimensional medium for conveying three-dimensional information and time-varying, dynamic processes, and of the producer's performance level for veridically depicting one's ideas. For example, in order to establish common ground, interlocutors may insist on modifications and standardizations to drawings used during collaborative problem solving (e.g., rules of linear perspective; Nathan, Eilam & Kim, 2007).

We were explicitly interested in the ways that college students learning about a scientific system of moderate complexity, the circulatory system, used drawings to depict their understandings after a self-guided (approx. 25 minutes), computer-based tutorial (following Butcher, 2005). Our analysis here focuses on how gesture and speech were employed in the service of the drawings as students explained them to an observer. We report here on the findings from two participants (supplemented by video in the presentations.)

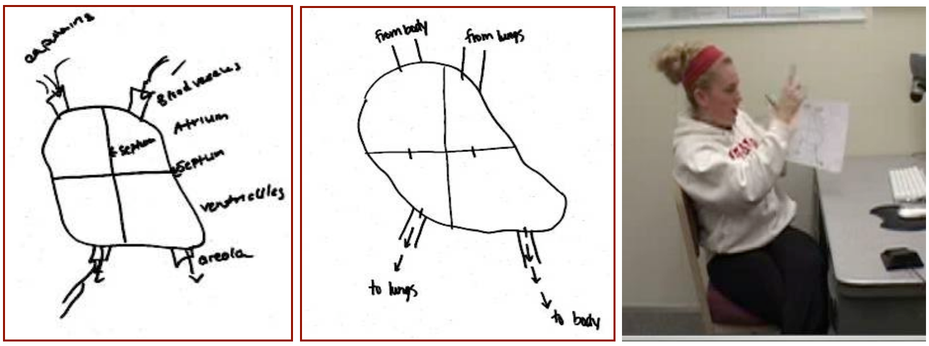

Figure 4. (a) A simple drawing with no dynamic processes conveyed by gesture. (b) A simple drawing that a student uses to provide (c) a simulation of the intended flow of blood to the body using gesture and speech ("And then this blood that from the right ventricle goes to the lungs. And then back into the heart from the lungs through this vein.")

Students may produce simple drawings that are similar in appearance (Figure 4) but mask wildly different mental models of the circulatory system. Figure 4a (Student A27) shows arrows entering the right and left atria at the top and arrows exiting the ventricles at the bottom. While pointing gestures index drawn and labeled elements such as the chambers and walls, no explanation of a time-varying process is provided, resulting in a very low score for the model (2 points out of 6). In contrast, Figure 4b (Student A14) shows a very similar drawing, with less detail (no labels) but through gesture and speech provides a rich account of the blood flow following two distinct pathways (from heart to lungs and back, and from heart to body and back) that receives a high score (6 out of 6 points). As Figure 4c shows, A14's gestures dynamically simulate blood flow to components of the system (e.g., lungs, body) that are not present in the drawing, but are invoked by gestures that move beyond the boundaries of the page.

Several insights emerge from the analysis of students' drawings and explanations. Methodologically, drawings are only a part of a student's rich, multimodal construction and must therefore be assayed in the context of the associated verbal and nonverbal information. Other examples show that even elaborate diagrams with arrows and labels suggesting the occurrence and direction of dynamic processes have limited assessment value without co-expressive gestures and utterances. As part of an emerging theory of the nature and functions of drawings for knowledge assessment, we find that these multimodal constructions (*psychological units* to Vygotsky, 1986; *growth points* to McNeill, 1992; *composite signals* to Engle, 1998; and *semiotic nodes* to Radford et al., 2003) are particularly evident when conveying time-varying phenomenon and causal relations.

Interactive drawing tools to support modeling of dynamic systems

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Dynamic computer modelling is a valuable way to learn about complex dynamic systems (Löhner, van Joolingen, Savelsbergh, & van Hout-Wolters, 2005; Spector, 2000). In a modelling task, students create an executable model in order to build and express their understanding of scientific phenomenona. Once the model is built, the data it produces can be compared to the expected or observed behaviour. The model can be modified depending on the outcome of this evaluation (Penner, 2001). Despite its benefits modelling is often experienced as difficult for students. For instance, students often fail at successful modelling behavior, because they do not use their prior knowledge while working on an inquiry modelling task (Sins, Savelsbergh, & Van Joolingen, 2005). Such observations highlight the need to support the modelling process. In the present paper, descriptions of drawing sketches of the modelled system as a means to support modelling are presented. Two approaches can be distinguished: drawing to prepare the model and drawing the model itself.

When drawing to prepare the model, a sketch serves a supporting and assisting role prior to "real" modelling. A sketch can be used to identify relevant variables and relations between variables. Figure 5 displays a sketch of a water tank that is then converted into a System Dynamics model. The drawing helps the learner to identify the relevant variables in the system, such as water level and outflow. These variables can then be converted into variables in the model. The drawing helps in this way with activating prior knowledge, and in constraining the model, based on the drawn elements. A sketch-based modelling tool can provide support in transforming a sketch into a model for instance by labelling model elements in the drawing.

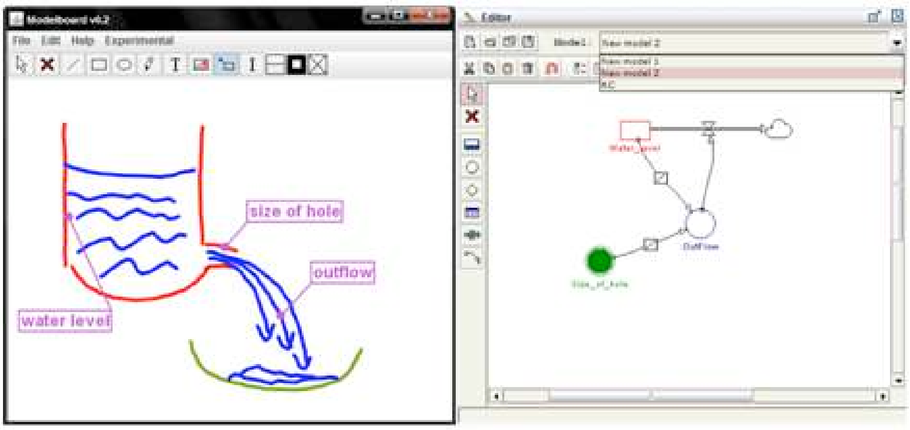

Figure 5. A sketch as a preparation for a (System Dynamics) model.

In order to investigate the suitability of this approach, we asked 68 students in upper secondary school to create drawings about the thermodynamics of the Earth: the earth is heated by the sun, making the earth radiate heat that is absorbed by the atmosphere, resulting in an equilibrium temperature. Close analysis of these drawings, identifying drawing elements and using principle component analysis shows that drawings give clear indications of learners' main views on heat and temperature, diverging into a radiation view and a heat transport view (Kenbeek, Van Joolingen, & De Jong, submitted), yielding complementary sets of variables to include in the model. Apparently drawing guide learners in making their views on the domain more explicit.

Alternatively, the learner-created sketch can be regarded as a model in itself. The drawing will not be transformed into another representation, but it is fully qualified as a learner's external representation of a phenomenon. In this case the drawing must adhere to some formal aspects, such as clear identification of objects in the drawing and their properties. Forbus and Usher (2002) put the burden of doing this with the learner who needs to identify the start and end of drawing and object (glyph in their terminology) and select a term from an ontology to describe the object. The approach presented here automates object identification by clustering strokes based on time, position, color and weight. A 95% agreement with human raters is reached using this method based on a set of drawings created by 37 students on two domains, a toy car (e.g. Figure 6) and a heating system (Leenaars, Bollen, & Van Joolingen, submitted). Sketch recognition techniques (Paulson & Hammond, 2008) can then assist object identification which can result in a formal model.

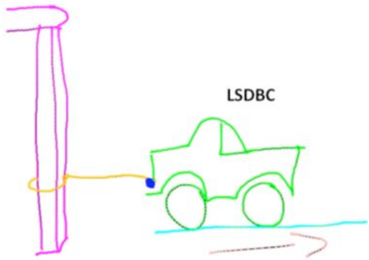

Figure 6. Drawing of the toy car system. Colors indicate automatic clustering results.

These two approaches provide a promising outlook on the use of drawings to support the complex task of modelling. The drawings collected in the two studies – for different purposes and in different domains, show that they are interpretable and give insight in learners' ideas about the domain modelled. Together the two approaches form a set of stepping stones that can be used to support the development of a modelling competency by novice modellers.

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