British Journal of Educational Technology Vol 44 No 1 2013 82–94
doi:10.1111/j.1467-8535.2011.01272.x

Using self-made drawings to support modelling in science education

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Abstract

The value of modelling in science education is evident, both from scientific practice and from theories of learning. However, students find modelling difficult and need support. This study investigates how self-made drawings could be used to support the modelling process. An experiment with undergraduate students (n = 37) at a predominantly technical university led to three conclusions. 1. Most learners created realistic rather than schematic drawings of real world systems. Furthermore, learners who represented situations realistically identified a greater number of important aspects of these situations than learners who represented them purely schematically. 2. Access to simulations during the construction of these drawings led to increased insight into the effects of variables that can be manipulated. However, participants with access to simulations thought of fewer important variables that were not explicitly available in the simulation than participants without this access. 3. Participants almost never drew multiple objects with a single stroke and generally drew objects sequentially. These patterns in the digital drawing process can simplify automatic sketch segmentation, which can be used to support learners in creating models from drawings.

Introduction

Modelling in science and science education

Models play a key role in scientific discovery and reasoning (Clement, 2000), and examples of their importance for scientific progress are numerous. Models were extensively used in the discovery and description of DNA's double helix structure (Watson, 1968; Watson & Crick, 1953) and were essential in the development of electromagnetic theory (Silva, 2006). Newton's mastery of the "modelling game" enabled him to write his magnum opus, *Philosophiæ Naturalis Principia Mathematica* (Hestenes, 1992). More generally, visual models are the dominant way of thinking in chemistry (Luisi & Thomas, 1990), and problem solving in physics is mainly a modelling process (Hestenes, 1987).

Practitioner Notes

What is already known about this topic

- Modelling plays a key role in scientific discovery and reasoning.
- Computer modelling in science education allows for a focus on the processes as well as the products of science.
- Students encounter difficulties during the modelling process and need to be supported.

What this paper adds

- Self-made drawings could be a good way to support the modelling process, because creating an informal drawing allows students to use their prior domain knowledge more easily than creating a formal model.
- Students who created a realistic drawing showed more prior knowledge activation than students who created an abstract drawing.
- Compared to students who only had access to a text, students who had access to a simulation during the creation of a drawing showed more insight into some variables of the system they represented, but found it more difficult to think of variables not adjustable in the simulation.

Implications for practice and/or policy

- Before students are asked to create a formal model of some domain, their prior domain knowledge may be activated by the creation of an informal drawing.
- When asking students to study a domain using a simulation, attention must be paid to the prevention of a focusing effect. This focusing effect may be attenuated by asking students to express their prior domain knowledge in a drawing before using the simulation.

Modelling is the process of building, using and evaluating external representations of systems. For an overview of these different modelling activities, see Löhner, van Joolingen, Savelsbergh and van Hout-Wolters (2005). The importance of modelling in scientific endeavours is one good reason to include it in science education curricula. Additionally, we can argue for a modelling approach to science education from a learning theoretical perspective. According to constructivism, which is currently the dominant view of learning (Mayer, 2004), "the mind produces [...] mental models that explain to the knower what he or she has perceived" (Jonassen, 1991, p. 10). The construction of an external model moves it from the mind of the modeller into the open world. This makes the model more concrete and puts it up for discussion, drawing out the social dimension of science (Penner, 2000). In the context of education, this allows students to clearly explain their ideas to teachers, peers and, perhaps most importantly, themselves.

Because models come in many shapes and sizes (eg, scale, symbolic and mathematical models) and can be used in the curriculum in different ways (Harrison & Treagust, 2000), we will briefly introduce the models and modelling context with which this paper is concerned.

This paper focuses on computer modelling in the context of inquiry learning. Computer models are particularly powerful, because learners can use simulations based on the models they create to gain more insight into the predictions of these models and, consequently, into the behaviour of the system they are studying. The use of computer modelling in science education has been widely recommended (Hung, 2008; Penner, 2000; Sins, Savelsbergh & van Joolingen, 2005). Inquiry learning is also commonly supported by computer simulations (Van Joolingen, De Jong &

Dimitrakopoulou, 2007), which means that both activities can be integrated in a single modelling and simulation environment. Co-Lab is an example of such an environment (Van Joolingen, De Jong, Lazonder, Savelsbergh & Manlove, 2005). In this environment, learners use simulations to explore hidden models and acquire knowledge in an active, constructive way (Dalgarno, 2001; Njoo & De Jong, 1993). Computer simulations offer learners a rich environment with low transparency (Swaak, Van Joolingen & de Jong, 1998), which means learners are able to gather a lot of information about the underlying model of the simulation by performing experiments, without being able to inspect this model directly. Learners can represent their knowledge of the system under study in their own model. Using simulations, learners can then compare the behaviour of their own model to that of the hidden model and adjust their own model as necessary.

Learners need support

To successfully create a computer model, learners have to understand the reference system and be able to express this understanding in a model; both lead to difficulties. While using simulations to try to understand the system's behaviour, learners typically encounter difficulties with hypothesis generation, experimental design, data interpretation and regulation of their learning process (De Jong & Van Joolingen, 1998). During model construction, learners often have problems using the model as a tool for understanding as opposed to an artefact that has to "work," often forgo use of relevant prior knowledge and find it hard to translate their knowledge into a computer model (Sins *et al*, 2005).

Another possible problem with simulation-based learning that has not received much attention in the literature stems from the fact that the hidden model on which a simulation is based is necessarily a simplified version of the real system. This means that learners will not be able to modify all the variables that may play a role in the real system. Limiting the number of variables that can be manipulated in the simulation is useful in ensuring that the learner is not overwhelmed by the system's complexity, but there is a risk that learners will have trouble thinking of other important factors in the system, that they cannot manipulate in the simulation. Learners' mental models will be restricted to aspects of the system that are explicitly represented in the simulation. This phenomenon, the *focusing effect*, is known to play a role in reasoning and decision-making (Legrenzi, Girotto & Johnson-Laird, 1993).

The need for support in constructive learning environments has been recognised (see Mayer, 2004 for an overview) and this support is the subject of many recent studies (eg, Mulder, Lazonder & De Jong, 2010; Van der Meij & De Jong, 2006; Wu, 2010). This paper explores a new form of support: self-made drawings.

Supporting modelling through self-made drawings

Making a sketch is a natural way to create an overview of a problem and sketches are often used to explain things to other people. Once we understand how something works, we "get the picture."

An important property of self-made drawings is that they are weakly expressive of abstraction (Cox, 1999). This means it is difficult or impossible to represent certain abstract relations with them, which forces learners to make abstract relations more concrete. For example, it is impossible to represent just the abstract relation of a fork and a plate being next to each other in a drawing. The fork has to be drawn either to the left or to the right of the plate, making the relation more concrete (Mani & Johnson-Laird, 1982). Another example: when creating a drawing representing "a window in a wall," choices have to be made about properties and relations that were implicit in the description, such as the size and location of this window relative to the wall.

In the context of computer modelling, making a sketch could help with the three main problems identified by Sins *et al* (2005): learners only try to make the model "work" instead of using it for understanding, they often do not use prior knowledge, and—when they *do* use prior knowledge—have trouble expressing it in the modelling language. Because a drawing does not have to be made to work, learners can focus on using it to understand the objects and relations in the system they are representing. It is simpler for novice modellers to express knowledge in an informal sketch than in a formal model, which may encourage them to represent more of their prior knowledge. In this way, a self-made drawing can provide the basis for the construction of a computer model, giving learners a chance to organise their prior knowledge before expressing it more formally. Ainsworth's (2006) framework for learning with multiple representations provides further insight into the use of informal drawings in combination with formal models.

Finally, the learning environment could support the learner during the translation of a drawing to a formal model. This support could consist of general advice, such as "think about the sort of variables you can use in your model to represent important objects from your drawing," but could be more effective if the learning environment understood, to some extent, what the learner had drawn. Suppose the learner used a graphics tablet to make a drawing of the solar system on the computer. Depending on how well the system understands the drawing, it could give feedback on the absence of important objects or relations (eg, the planets' orbits are not drawn), identify misconceptions (eg, all planets circle the sun in the same orbit) or even animate the drawing based on the implicit formal model that is represented. If the learning environment had enough domain knowledge, the drawing could *be* the model. This last approach is used by Forbus, Usher, Lovett, Lockwood and Wetzel (2011) in their design of CogSketch. This sketch understanding system is backed by a large knowledge base containing information about properties of and possible relations between objects. This allows the program to use the spatial information from the sketch in combination with its knowledge of the objects that are represented to reason about the relations depicted in the drawing. CogSketch currently skips the difficult steps of sketch segmentation (automatically dividing a drawing into meaningful groups) and sketch recognition (recognising what is represented in these groups), by asking the learner to divide the drawing into objects and label these objects manually. This allows CogSketch to understand sketches in almost any domain, but makes working with the program less straightforward than creating a normal sketch. This paper will explore which properties of drawings can be used to automate sketch segmentation, allowing a more natural interaction with the learning environment.

Research questions

The goal of this study is to answer a number of questions related to supporting the scientific modelling process with self-made drawings. These questions will be introduced with an example of a typical modelling activity, in which a college student is asked to create a system dynamics model of the temperature in a house. The situation is described in the following short case text:

> "A house is warmed through central heating, but also loses heat to its external environment, for example through windows and poorly isolated walls. The house's central heating unit is controlled by a thermostat, which switches the heating on when the room temperature drops too far below the preferred temperature and switches it off again when the temperature becomes too high."

Besides the textual description of the system, the student also has control over a simulation of the house. This simulation shows the changes in temperature in the house during the day and lets the student control certain parameters of the model. In this case, the student can change the preferred indoor temperature, the average outdoor temperature, the volume of the house and the surface area of the windows.

Drawing a sketch could help the student discover the components and relations in the system that should be included in the model. The drawing's usefulness may depend on how the student chooses to represent the system. Is the drawing realistic or schematic? Does the drawing only contain information that is present in the case description or does it also reflect prior knowledge and additional assumptions made by the student? How are non-spatial relations represented? In summary:

1. How do students commonly represent real-world systems in a drawing and is this related to their ability to activate relevant prior knowledge?

Two effects are expected from use of a simulation. First, using the simulation should provide insight into the important variables and relations in the system. We wish to confirm this is the case, because otherwise the domain is perhaps too familiar or too simple for the student and little attention would have to be paid to the simulation. Second, the student's mental model of the system may be restricted by the focusing effect. This would mean that the student finds it difficult to think of other important aspects of the system after using the simulation. Because activating and organising relevant prior knowledge are goals of making a drawing, the best time to create it depends on a possible focusing effect of simulation use. These considerations lead to the next two research questions:

2. Do students with access to a simulation express a better understanding of important variables and relations in the studied system than students without such access?
3. Do students with access to a simulation mention fewer important aspects of the studied system that cannot be manipulated in the simulation than students without such access?

Finally, we are interested in finding properties of drawings and common patterns in the way they are created that can be used to simplify the process of automatic segmentation. Improving automatic segmentation could lead to a more natural interaction with a sketch understanding system. Thus, the final research question is:

4. Which properties of (the creation of) drawings could be useful for automatic sketch segmentation?

Method

Participants

Thirty-seven undergraduate students at the University of Twente, who had all taken physics courses at the highest level of high school (VWO, Dutch pre-university education), participated in an experiment that lasted 30–45 minutes. Participants were not asked for their age, but had been in college for 1.9 years on average ($SD = 0.87$), which means the average age was approximately 20 years. Twenty-five of the participants were male and 12 were female. Most participants studied technical subjects: applied physics ($n = 11$), industrial design ($n = 8$), civil engineering ($n = 4$), advanced technology ($n = 3$), psychology ($n = 3$), health sciences ($n = 2$), mechanical engineering ($n = 2$), technical medicine ($n = 2$), public administration ($n = 1$) and educational science ($n = 1$). Students who needed them received "participant credits" for their participation, but most received no payment or other reward.

Materials

Participants worked with a laptop and drawing tablet in an integrated drawing and simulation environment that was created specifically for this study. Figure 1 shows this environment. Participants could use pencil and eraser tools to create drawings and a labelling tool to make notes on certain aspects of their drawing. These tools are described in the next sections. Detailed logs of all the users' interactions with the software were automatically saved.

The environment offered three tutorials, which taught participants to use the drawing tablet and the software, followed by two cases.

First tutorial: connecting the dots

The first tutorial consisted of a simple "connect the dots" worksheet that familiarised participants with the pencil and eraser tools. The pencil tool responded to the pressure that was applied to the

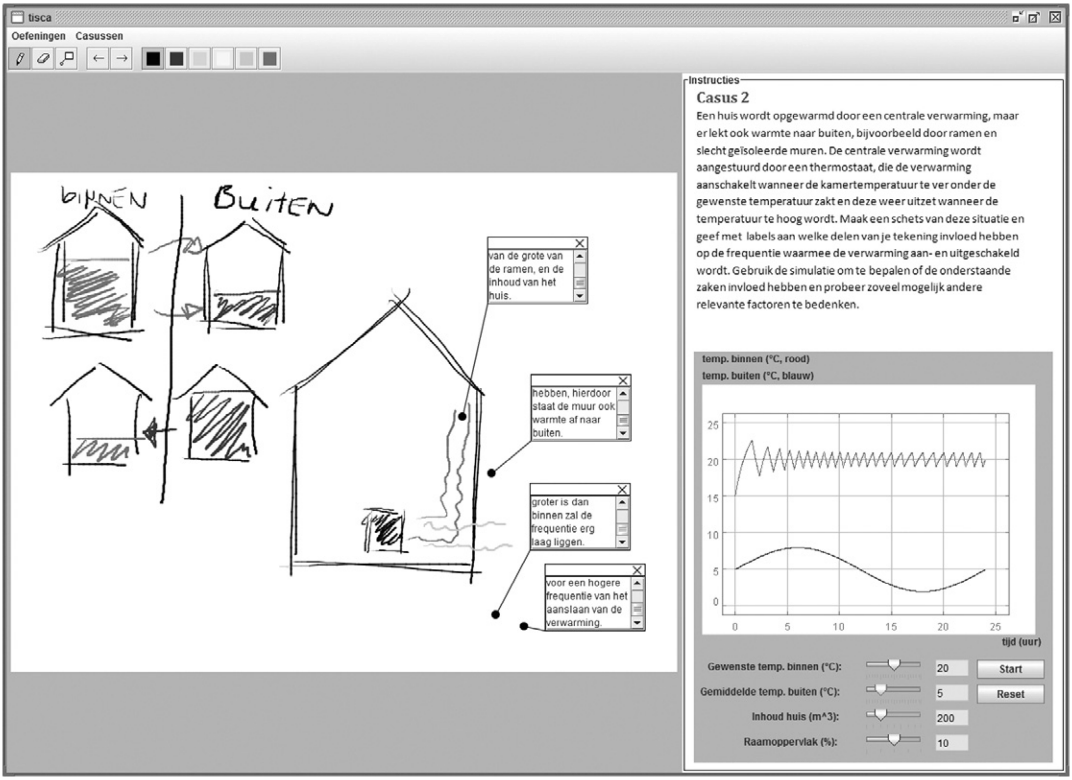

Figure 1: Screenshot of the simulation and drawing environment in which participants worked.

pencil, drawing a thicker line if the participant pressed harder on it. The eraser tool allowed only stroke-wise deletion. This means that participants could not delete just a part of a line they had drawn, but only the line in its entirety, which simplifies sketch analysis. Undo and redo functions were also available.

Second tutorial: writing
The second tutorial served two functions: offer participants writing practice and collect background information. Participants were asked to give handwritten information about their gender, their main subject, how long they had been in college, and their grades for maths and physics in high school.

Third tutorial: labelling
This tutorial introduced the labelling tool and prepared participants for the two cases. The labelling tool allowed participants to add labels to any part of their drawing. Text could be typed in these labels and they could be moved around after they were created. Four labels are shown in the drawing in Figure 1.

Participants were shown a picture of water flowing from a tap into a leaky bucket and asked to add labels to those parts of the picture that were relevant if one wanted to calculate how much water was in the bucket after a specified time. For instance, the discharge of the tap and the size of a hole in the bucket are relevant parts of the picture. This task, identifying and labelling relevant components of a system, was also an important activity during the two cases.

First case: toy car
Participants received the following instructions (translated from the Dutch original):

"A toy car is connected to a table leg with an elastic string. The car contains a small engine that produces a constant forward force on the car. The engine is switched on and the car starts to move away from the table leg, causing the elastic string to be pulled tight. Because the string pulls the car backwards, the car may start to oscillate, but it is also possible that it slowly comes to a halt without oscillating. Make a sketch of this situation and use labels to identify those parts of your drawing that have an effect on whether or not the car will oscillate. Decide whether the variables mentioned below are relevant, and try to think of as many other relevant variables as possible."

The instructions that follow were either some suggestions for relevant factors (text-only condition) or a simulation that allowed participants to manipulate these same variables (simulation condition). These variables were:

- Mass of the car;
- Force produced by the car's engine;
- Length of the relaxed elastic string; and
- Force constant of the elastic string.

In the simulation condition, which used a simulation created in SimQuest (Van Joolingen & De Jong, 2003), participants could use sliders to set values for these variables within a given range. The results of the simulation were plotted in a time–distance graph. Finally, participants were asked to specify what the effects of the relevant variables were; for example, would a greater mass of the car lead to a greater or lesser probability of oscillation?

Second case: temperature regulation

The second case had the same structure as the first case. Participants received the case description about heating a house that can be found in the Introduction and were asked to identify those parts of the system that had an effect on the frequency with which the radiator was switched on and off. Below the description were again either some suggestions or a simulation with the following variables:

- Preferred temperature in the house;
- Average outside temperature;
- Volume of the house; and
- Total surface area of the windows.

When the simulation was run, the indoor and outdoor temperatures during the day were plotted in a time–temperature graph. The outdoor temperature varied around the average outside temperature and was based on a sinusoid with a 24-hour period. Results of this simulation can be seen in Figure 1.

Procedure

Participants were randomly assigned to either the text-only ($n = 19$) or the simulation group ($n = 18$). After receiving instruction from the experiment leader on working with the drawing tablet, participants completed the three tutorials and two cases. There was no time limit for the tutorials or cases and participants were told they could proceed to the next task when they felt they were done with the current one.

Analysis

Representation

Drawings were classified as either realistic or schematic representations. Drawings were only classified as schematic when it was impossible to recognise that a car (first case) or a house (second case) was being represented. For instance, this was the case when the toy car was drawn as a block with arrows representing the different forces acting upon it. The number of drawings that contain formal elements, such as the arrows representing forces, was also examined.

Also of interest was how much of the situation was represented by participants; for example do participants draw the ground in the first case and the radiator in the second case? Whether or not participants represent these aspects of the situation could have an effect on which relevant aspects of the situation they find. For instance, when participants draw the ground in the first case, they could realise that it is not necessarily flat (nothing is said about this in the case description), which would have an effect on the movement of the car.

Finally, an independent two-sample *t*-test was used to discover if there was a relation between representation style (realistic or schematic) and prior knowledge activation (number of other factors mentioned). Cohen's *d* was used as a measure of effect size for all comparisons (Cohen, 1988).

Simulation effects

Participants' expressed understanding of the different variables and relations playing a role in the cases was measured by scoring their drawings on four different aspects in both cases. For each of these aspects, participants received either 0 or 1 point(s).

For the first case, participants were scored on correctly assessing the effect of each of the four mentioned variables (mass of the car, force produced by the engine, length of the relaxed elastic string and force constant of the elastic string) on whether or not the car would oscillate.

For the second case, participants were scored differently, because the effect of three of the four mentioned variables (preferred inside temperature, average outside temperature, volume of the house, total surface area of the windows) was not straightforward. Only the volume of the house had a clear effect on the frequency with which the heating was turned on and off. Participants received points for mentioning that the difference between preferred and outside temperature was relevant (as opposed to either one of these individually), for mentioning that the heating was always on or off in some situations and for mentioning that the frequency of the heater's on/off cycle depended on both the warming up and cooling down period.

Further details of this scoring system can be found in the Appendix. Using this system, each participant received a score ranging from 0 to 4 points for both cases. To make sure this scoring system was clear, one third of the participants' drawings were scored by a second rater. Interrater reliability was calculated using Cohen's κ (Cohen, 1960). For the first case, interrater reliability was high ($\kappa = 0.84$), and for the second case it was very high ($\kappa = 0.96$). Differences between the scores of participants in the text-only and simulation conditions were determined by using an independent two-sample *t*-test.

The number of other relevant factors participants thought of in each case was measured by simply counting the number of new factors that were mentioned. The difference between participants in the text-only and simulation conditions was again determined using an independent two-sample *t*-test.

Representation for automatic sketch segmentation

For the purpose of automatic sketch segmentation, only the drawings in the first case were analysed. The reason for this decision was that the houses that were drawn in the second case contained many elements such as doors and windows that could be seen as subgroups of a larger "house group." To meaningfully separate such a drawing into different groups would require an hierarchical approach that is outside the scope of this exploratory research.

Not only the drawings themselves were saved, but also the logs of the drawing process. Therefore, it was possible to examine exactly how each drawing was created. Exploratory, manual analysis of these logs was used to find drawing patterns that could be useful for automatic sketch segmentation.

Results

Representation

The toy car in the first case was represented realistically by 35 out of 37 participants (95%). Arrows representing the forces that played a role in this situation were added by 17 participants

(46%). None of the participants chose to represent the car with a free body diagram of just the block and the forces acting upon it; all participants represented the table leg and the elastic string explicitly. The only other aspect of the situation that was frequently represented by participants was the ground. This was drawn by 12 participants (32%).

The house in the second case was represented realistically by 29 out of 37 participants (78%). Arrows were used to represent air flow or heat transfer by nine participants (24%). Much more variation in the way participants represented the situation existed in the second case than in the first case. Some participants drew a house with a see-through wall on the front side, others drew solid houses; some drew multiple stories, others drew just one room; some drew the house in 3D, others in 2D.

In contrast to the toy car in the first case, enough participants represented the house schematically to allow meaningful comparison of this group with those that represented it realistically. Although the eight participants that represented the house schematically were evenly divided between the simulation and text-only conditions (four in each group), there was a relation with the number of other factors these participants mentioned. They mentioned significantly fewer other factors than participants who represented the situation realistically ($t = 2.3$, $p = 0.03$, $d = 0.74$).

Simulation effects

Table 1 shows the means of the scores and number of other factors mentioned for each condition in both cases. For the first case, the difference between the scores of the text-only and simulation groups was significant ($t = 7.1$, $p < 0.0005$). As hypothesised, participants in the simulation group scored higher ($d = 2.39$) than participants in the text-only group. The difference between the number of other relevant factors participants mentioned was also significant ($t = 2.7$, $p = 0.006$). Participants in the simulation group thought of fewer other relevant factors than those in the text-only group ($d = 0.91$).

For the second case, the difference between the scores of the text-only and simulation groups was also significant ($t = 2.6$, $p = 0.007$). Participants in the simulation group scored higher than those in the text-only group ($d = 0.87$). There was a trend towards participants in the text-only group mentioning more other factors than those in the simulation group, but this was not significant ($t = 1.6$, $p = 0.06$, $d = 0.54$). Closer inspection of the log files showed that five out of eighteen participants in the simulation group did not use the simulation before labelling the factors they regarded as important. Only after they had created a drawing of the situation and labelled those aspects of the drawing they believed were relevant, did they start using the simulation to gain more insight into the effects of the variables that could be manipulated. This means that when they were thinking of the other relevant factors, they had the same information as those in the text-only group. When these five participants are omitted from the comparison, the difference regarding the number of other factors mentioned is significant ($t = 2.8$, $p = 0.005$, $d = 0.96$).

Table 1: Scores and numbers of other factors mentioned

	First case: toy car		*Second case: temperature regulation*	
	Score	*Number of other factors*	*Score*	*Number of other factors*
Text-only	1.21 (0.85)	1.89 (1.37)	1.11 (0.88)	3.21 (2.12)
Simulation	3.06 (0.73)	0.89 (0.83)	1.89 (0.96)	2.11 (2.05)

Note: Values are means of the scores and number of other factors mentioned for the text-only and simulation conditions in both cases (standard deviation in parentheses). The minimum and maximum scores were 0 and 4 respectively.

Representation for automatic sketch segmentation
Only eight participants used multiple colours in their drawing. Those participants mostly used different colours for different elements of their drawing.

Most participants represented the situation in a very simple way: on average 23 strokes were used to draw the scene with the table, the toy car and the elastic string. The median number of strokes is 14. The large difference between these numbers was caused by a single participant who used 143 strokes. Only four participants filled small parts of their drawings; all other drawings consisted exclusively of outlining strokes.

Different objects were almost always represented with different strokes. Only one participant used one stroke as part of two different objects: the string and the toy car.

Participants usually drew objects one at a time. For instance, they rarely drew part of the table first, then (part of) the toy car and then completed the table. In numbers: 97.4% of all strokes were either part of a new object or part of the same object as the previous stroke; only 2.6% of strokes were part of an object that had been previously started, but to which the previous stroke did not belong.

Discussion

Almost all participants represented the first case realistically rather than schematically and most did the same for the second case. Participants who did represent the second case schematically mentioned significantly fewer relevant factors than those who represented it realistically. The schematic drawings contained fewer elements (eg, no windows or doors were drawn), which could explain why participants who created them did not think of as many important aspects as those who made more realistic drawings. This explanation is consistent with the value of concrete representation in drawings as discussed by Cox (1999). However, it is important to note that no explicit hypothesis was proposed about the effect of realistic or schematic representations, and that representation style was not an independent variable in this study. This means that no causal link can be assumed, and further research would be needed to determine the effect of representation style on activation of prior knowledge. Furthermore, there was much more variation in the representations of the second case than of the first case, which indicates that findings about representation styles cannot be generalised at this stage.

Participants with access to simulations expressed a better understanding of the variables they could manipulate than participants in the text-only condition. This indicates that the domains were sufficiently complex and use of the simulations contributed to participants' understanding of the domains. A significant focusing effect (Legrenzi *et al*, 1993) was found in the first case, with participants in the simulation condition mentioning fewer other important aspects of the system than participants in the text-only condition. The focusing effect was not significant in the second case. Closer analysis of the log files revealed a likely reason for the disappearance of this effect: five participants in the simulation condition (compared to just one in the first case) made their drawing and labelled the aspects they considered important before using the available simulation. This approach enabled them to avoid the focusing effect that was significant for participants that used the simulation before thinking about other important factors. These findings indicate that learners should create a drawing of the system and think about important factors before using a simulation. This sequence lets learners activate and organise their prior domain knowledge before focusing on gaining a deeper understanding of the role of those variables that can be manipulated in the simulation.

In the drawing logs, some interesting patterns were found that could be used for automatic segmentation of the drawings. When colours were used, these gave clear hints about the different objects in the drawings, but their use was uncommon. The simplicity of the drawings—most participants used few strokes and infrequently used strokes for filling—makes automatic segmentation easier. The two most promising findings are that strokes were almost never part of more than one object and that participants drew one object at a time. The first finding means that it is not necessary to segment the drawing at the pixel or point level, but that segmentation can be done by assigning entire strokes to groups (eg, the first three strokes belong to the car group, the next two strokes belong to the table group). The second finding suggests that it is possible to accurately segment drawings by going through each stroke chronologically and determining whether it is part of the same object as the previous stroke or part of a new object. A simple algorithm using this approach was implemented and found to correctly classify over 90% of strokes. Note that caution is needed when generalising these findings to other domains, settings or learners as they are based on drawings of a single domain by a relatively small set of participants.

The results of this exploratory study on supporting the scientific modelling process with self-made drawings lead to tentative recommendations for educational practitioners and provide directions for future research. Educators using simulation-based approaches should be aware of the focusing effect. This study showed that using simulations can lead to greater insight into adjustable variables, but made it more difficult to think of relevant domain variables that were not explicitly present in the simulation. Letting students create drawings of the domain before using the simulation could serve to activate their prior knowledge and alleviate the focusing effect.

Future research could use the findings regarding the best sequence for creating a drawing and using a simulation to actually integrate the creation of drawings in a modelling task. The results of such a study could show if self-made drawings can in fact be used to overcome the problems with prior knowledge activation and representation during a modelling task that Sins *et al* (2005) discuss. More insight into the effects of realistic and schematic representation styles on prior knowledge activation could be gained from a study in which representation style is the independent variable. Such a study could inform us on whether realistic representation styles should be encouraged over schematic representation styles for situations in which prior knowledge activation is the goal. Finally, future research on sketch segmentation and recognition could improve the support that learning environments can offer during the creation of a drawing. Advances in these areas could make the construction of simple computer models more similar to creating a sketch than to programming a computer.

Acknowledgements
We would like to thank Annika de Goede for being a first-rate second rater.

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Appendix

Scoring system

First case: toy car

Two out of four of the mentioned factors have an effect on whether or not the car will start to oscillate: the mass of the car and the force constant of the elastic string. Both of these factors are positively correlated with the chance the car will oscillate.

Factor	*Effect on oscillation*	*Points*
Mass of the car	The mass of the car has an effect. Larger mass means the car is more likely to oscillate.	Not relevant: 0 Negative correlation: 0 Positive correlation: 1
Force produced by the engine	The force produced by the engine has no effect on whether or not the car will oscillate. It does have an effect on the amplitude of the oscillation.	Relevant: 0 Not relevant: 1
Length of the relaxed elastic string	Length of the relaxed elastic string has no effect on whether or not the car will oscillate.	Relevant: 0 Not relevant: 1
Force constant of the elastic string	The force constant of the elastic string has an effect. Larger force constant means the car is more likely to oscillate.	Not relevant: 0 Negative correlation: 0 Positive correlation: 1

Second case: temperature regulation

All four of the mentioned factors have an effect on the frequency with which the radiator is switched on and off. However, the effect of these factors is not as straightforward as in the first case: there is a lot of interaction between the relevant variables. The volume of the house is an exception to this rule: larger volume leads to a lower frequency.

Factor	*Effect on frequency*	*Points*
Preferred inside temperature Average outside temperature	The effects of the preferred temperature and the average outside temperature don't mean much. However, the difference between these two is relevant.	Participant mentions difference between these two as relevant: 1
Volume of the house	The volume of the house has an effect. A larger volume leads to a lower frequency.	Not relevant: 0 Negative correlation: 1 Positive correlation: 0
Total surface area of the windows	The total surface area of the windows has an effect, but this effect is not straightforward. A larger surface can lead to both a higher and a lower frequency in different conditions.	No points awarded

Participants were awarded points for mentioning two other aspects of the situation:

- The heater is always on or off in certain situations: 1 point
- The frequency of the heater's on/off cycle depends on both the time it takes to warm up the house and the time it takes for the house to cool down. This is especially relevant when considering the effect of the total window surface. A larger window surface often means it takes more time for the house to warm up, but less time for it to cool down: 1 point