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Stimulating Scientific Reasoning with Drawing-Based Modeling

Abstract

To see how a drawing-based modeling tool can be used to stimulate scientific reasoning, we redesigned an existing modeling tool and accompanying instructions during four iterations. During each test four to six lower grade high school students worked on an assignment in the domain of evolution while their conversations were recorded. After each test, the user interface and instructions were adjusted based on students' remarks and the teacher's observations. Students' conversations were analyzed on reasoning complexity as a measurement of efficacy of the modeling tool and the instructions. The findings were also used to compose a set of recommendations for teachers and curriculum designers for using and constructing models in the classroom. Our findings suggest that to stimulate scientific reasoning in students working with a drawing-based modeling tool for the first time, the emphasis during instruction should be placed on the workings of the tool, not on the assignment itself. It is also recommended to keep the amount of options during this first time to a minimum, to minimize distractions and students' insecurities when not using a particular function. The teacher's role is to scaffold students' reasoning to draw out more detailed explanations for phenomena.

Due to the advance of science and the integration of science in our daily life, scientific literacy is becoming more and more important to be able to make informed decisions in today's society (DeBoer, 2000; Laugksch, 2000). What scientific literacy exactly entails has been subject to discussion, but there seems to be consensus on the inclusion of scientific reasoning (Arons, 1983; Durant, 1994; Laugksch, 2000; Miller, 1983): the reasoning patterns scientists use to get from question to answer.

Scientific reasoning skills play an important role in the ability to construct scientific concepts and do science and (if they develop at all) are formed during adolescence (Lawson & Clark, 2000). It is therefore important to stimulate scientific reasoning early in life. This is reflected in the advance of inquiry-based learning, in which learners construct knowledge, similar to the way scientists do. This method stimulates scientific thinking by having students construct their own hypotheses, design their own experiments and draw their own conclusions (van Graft & Kemmers, 2007). Inquiry learning can be implemented in many different ways.

Models and modeling are considered fundamental elements of scientific literacy (Louca & Zacharia, 2012) and they can be used to engage students in scientific inquiry. While students construct models they learn to make concrete representations of abstract ideas and their underlying causes (Windschitl, Thompson, & Braaten, 2008) which can motivate them to use scientific reasoning skills. The Dutch national expertise center for curriculum development (SLO) has published a new science knowledge base (Ottevanger et al., 2014) in which the importance of understanding models is emphasized. According to this report, students in the lower grades of secondary education (comparable to grades 7 to 9 of high school) should learn what models are and how they are used. The two main goals the SLO wants to achieve are an understanding of scientists' caution when drawing conclusions and the ability to discern the parts of a model that are relevant. This should contribute to students' understanding of the nature of science.

The relationship between models and scientific reasoning does not just go one way: models can also be used to teach scientific reasoning skills. Louca & Zacharia (2012) showed in a review of all relevant articles between 1990 and 2011 that model-based learning in science education affected cognitive, metacognitive, social, material and epistemological skills positively, which in turn contributed to students' learning. Modeling (the practice of making models instead of only using them) as a learning method is more effective at attaining conceptual and operational understanding of the nature of science and developing reasoning skills than current other learning tools (Harrison & Treagust, 2000). Modeling can also provide opportunities for students to think and discuss in a scientific way about their ideas (Rouwette, Vennix, & Thijssen, 2000).

To see how a modeling tool can be used in the classroom to teach about models and stimulate scientific reasoning we have redesigned a computer program called SimSketch (Bollen & van Joolingen, 2013). In SimSketch students draw objects, assign characteristics and behaviors to those objects and can see how the interaction between objects takes place by running a simulation. This practice is called drawing-based modeling. Students working in pairs on a modeling assignment will naturally share their thoughts about the modeling process with each other. Their conversations can show what elements in the teacher's instructions and the modeling environment facilitate, and what elements inhibit scientific reasoning.

Theoretical & Empirical foundations

SimSketch combines two practices: drawing and modeling. Modeling is a goal in itself but also takes shape as a tool that provides students with the opportunity for scientific reasoning and discussing ideas. In this section I will outline the use of models in inquiry learning, discuss the use of drawing in science education and show how these methods are combined in drawing-based modeling. Subsequently, I will discuss the methods used to structure and improve the context and instructions given to the students.

SimSketch

Modeling.

Inquiry learning with models entails that students don't conduct their experiments on real objects or situations, but on models of reality. These models can be anything from miniatures to computer simulations. Computer models are not abundantly used in education, though their influence in the classroom could be great. Computer models can contain enormous amounts of information and can prove to be accurate models of reality, or in the way the outcomes differ from reality show how unaccounted variables influence the studied processes (Frigg & Hartmann, 2009). These are the same reasons why computer models are used in scientific practice.

Using computer models in inquiry learning is beneficial for students as well as teachers. Computer models allow students to manipulate experimental variables with ease and produce results that are more predictable and easier to visualize (Rutten, van Joolingen, & van der Veen, 2012). Constructing models in addition to using them is a way for students to experience research in the same way it is performed by many scientists (Frigg & Hartmann, 2009), possibly stimulating them to use scientific reasoning patterns. For teachers, computer models are relatively easy to implement in the classroom, because no equipment is needed apart from the computers.

Computer modeling in the lower grades of high school education, however, cannot involve the amount of mathematics and abstractness as modeling in scientific research. In order to make modeling accessible to younger students, graphical representations of models can be used. In these models the underlying mathematics are invisible and users directly interact with the objects, allowing them to immediately see how changing a variable influences the outcome of the experiment.

Previous research on scientific reasoning with graphical represented models showed that students do spend a lot of time on scientific reasoning, but that they do not use a systematic approach and often forget about the hypothesis (Löhner, van Joolingen, Savelsbergh, & van Hout-Wolters, 2005). This study was about students working with models as a tool, not students constructing the models themselves. The studies reviewed by Louca & Zacharia (2012) suggest that the construction of models has even more positive influences on students' learning than just using them. The process of constructing models while discussing with a peer could support students' reasoning processes.

Drawing.

Drawing has been proposed as an engaging way to learn in science because it makes students reason in various ways and allows them to compare their drawing with observations, measurements and emerging ideas (Ainsworth, Prain, & Tytler, 2011). This can help students to consciously relate different concepts and behaviors to each other. Ainsworth et al. suggest that drawing should be a key element in science education, since drawings can be used to enhance engagement, to learn to represent scientific ideas, as a learning strategy and to reason in science. When students draw, they choose specific features on which they focus in their drawing. The selection of these features is a representation of their reasoning about scientific concepts.

Drawing-based modeling.

The combination of drawing and modeling leads to a method called drawing-based modeling (van Joolingen, Bollen, & Leenaars, 2010). Students can make their own drawings and assign behaviors to the objects they draw to create simulations, without the need to understand the mathematics behind them. Drawing-based modeling goes further than pen-and-paper drawings: it enables students to transform their drawings into simulations, allowing them to convey more complex ideas in an understandable way and observe changes in outcome when changing variables.

Learning about a model takes place in the manipulation as well as the construction of the model (Frigg & Hartmann, 2009). Drawing-based modeling allows students to not just work in a set modeling environment, but to design their own experiments and draw the objects they need. Previous research on drawing-based modeling has shown that students make higher quality drawings when they first make their own, and then combine their drawing with that of another student, compared to when they are working on their own and the missing elements of their drawing are pointed out to them (van Joolingen, Bollen, Leenaars, & Gijlers, 2012). How drawing based-modeling influences their scientific reasoning, we do not yet know.

Instructions & Assignment

The initial oral instructions, the assignment and the assistance given to students while working on the assignment are designed and redesigned to ensure that students spent the maximum amount of time on scientific reasoning and experimenting. We make use of several theories and practices to support this. In this section an overview of the most important theories and practices is given.

Context-based & inquiry learning.

The assignment makes use of both context-based and inquiry learning. Context-based learning aims at providing an interesting context for students to work with, so they see the applications and relevance of their work in relation to real-world phenomena.

Inquiry learning lets students self-regulate their learning, supported by the teacher. This way of learning should increase students' motivation and interest in science, while they learn to perform (experimental) procedures similar to those done in science (Bell, Urhahne, Schanze, & Ploetzner, 2010).

Combining these two methods results in an assignment that lets students explore and experiment within a given context.

Scaffolding.

Though minimal guidance would suggest that more input is needed from the student (and hence more scientific reasoning would take place), evidence from multiple empirical studies indicates that minimally guided instruction is not as effective and efficient as teaching in a way that puts emphasis on guiding the students' learning process (Kirschner, Sweller, & Clark, 2006). For inquiry learning to be successful, extensive scaffolding and guidance is needed (Hmelo-Silver, 2007).

Scaffolding can be defined as the process by which a more knowledgeable person (usually a teacher) assists learners to effectively deal with problems that would be too difficult to tackle on their own (Quintana et al., 2004). This assistance can range from strategic guidance to performing difficult parts of a task. An important thing to note here is that scaffolding does not mean that teachers should give away answers: assistance should be supporting, not dictating.

Research Question

The aim of this study is to determine how we can enhance the scientific reasoning skills of students engaged in a modeling task, using a drawing-based modeling tool. We want to see how drawing objects and building a model affects the amount and complexity of reasoning, and what parts of the assignment and modeling environment can stimulate or inhibit scientific reasoning. This can be formulated as the following research question:

How can we stimulate the scientific reasoning processes of students using a drawing-based modeling tool?

This study will result in a drawing-based modeling tool that incorporates the accumulated knowledge about using and constructing models in the classroom, as well as a set of recommendations for teachers and curriculum designers.

Methods

In this design-based research study we have redesigned the drawing-based modeling tool SimSketch to make a user-friendly modeling tool in which students can make their own simulations by drawing objects and assigning behaviors. Additionally, an assignment in the domain of evolution has been designed to accompany the SimSketch environment.

The assignment is loosely based on the story of natural selection on the snail species *Cepaea nemoralis* (Cain & Sheppard, 1952). These snails are polymorphic in shell color and banding, with certain morphs appearing more in certain areas. This is believed to be the caused by thrushes, who hunt the snails by sight. This results in snails having a shell color that matches the background color of the area in which they live.

For the assignment students make a model of snails in two adjacent areas: a green area to represent forest and a red area to represent clay. Birds can be set to hunt by sight, which means they will pick those snails that have the highest contrast to the background color. Over time, this results in a population of green snails in the green area, and red snails in the red area (see figure 1). Ideally, students working on this assignment would observe the changes in color and attribute them to the right causes. The emphasis of this study, however, is on the reasoning complexity students express, not how right or wrong their assumptions and conclusions are.

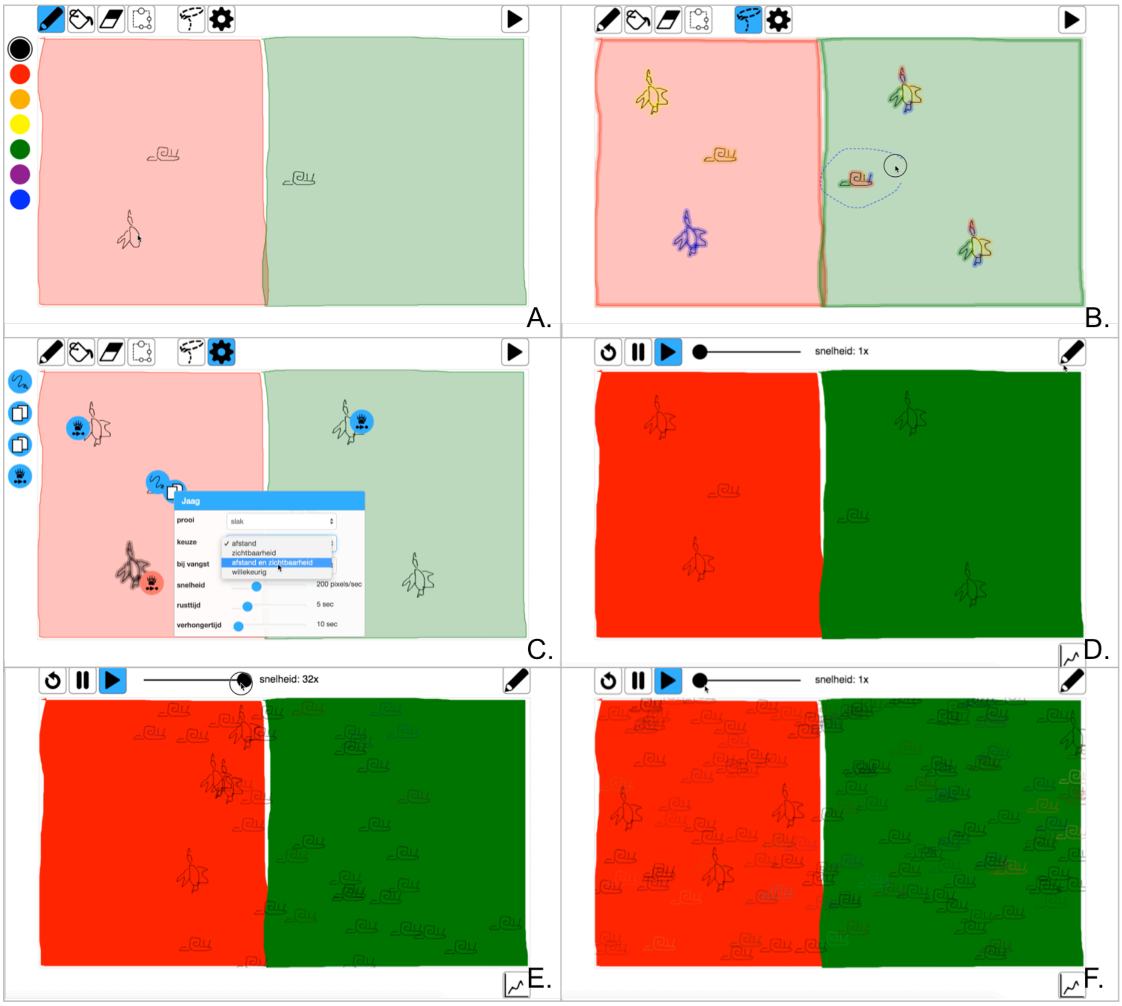

Figure 1: Example of successful modeling of snail populations. A: drawing two areas (red for clay and green for forest), snails and birds. B: selecting those drawing strokes that should be considered by the program as one object (lines associated with a single object share the same color). C: Assigning behaviors by dragging the icons from the left onto the objects. adjustments can be made by clicking on the icon. D: starting the simulation. E: shortly after starting the simulation. The snails have multiplied and are spreading. F: After the simulation has run for a few minutes there is a population of red snails in the red area and a population of green snails in the green area.

The design of SimSketch and the assignment have gone through multiple iterations. For each iteration, students from grade 1 to 3 of HAVO and VWO (the two highest variants of the three secondary education streams of the Netherlands) worked on the assignment in SimSketch during one class period of fifty minutes. Of these fifty minutes, approximately fifteen were spend on introducing the context and explaining the workings of SimSketch, thirty on modeling and five on discussing what students thought of the assignment and SimSketch. The researcher took on the role of the teacher during this time.

Students' scientific reasoning was analyzed to determine what elements in the combination of assignment and modeling tool have an influence on scientific reasoning. The subject of the assignment is in the domain of evolution, for this is one of the key theories of biology.

During most tests students worked in pairs, but on two computers. They first made their own drawing and then explained their drawings to each other to come to a joint drawing. This follows from the research of van Joolingen et al. (2012), which showed that students who combine their drawings produce higher quality drawings than students who work individually. During the third test, however, there were not sufficient laptops available for each student. Students therefore worked in pairs on one laptop. This did not seem to influence the amount of discussion about the model. An additional benefit of working in pairs is that students naturally share their thought process, allowing us to follow their reasoning without having to force them to think aloud.

Participants

Participants were selected from a grade 1 class (HAVO/VWO level), two grade 3 classes (HAVO level) and a grade 2 class (HAVO level). These classes were all taught by the same biology teacher. The teacher of these classes selected students at random, or from those students who wouldn't have a disadvantage from missing a regular biology class. No students had previous experience with drawing-based modeling and no student participated in a test twice.

Instructions & Assignment

The context students work with for the assignment is presented orally as well as in written text. For all tests but the first, students simulated a population of snails in two different areas. These areas are clay (red) and forest (green). The 'genes' that regulate the color of the snails' shells can mutate, resulting in multicolored snails. The snails are hunted by birds, which (if they hunt by sight) will eat the snails that are the least camouflaged. This will result in a population of green snails in the forest and red snails on the clay. For the first test the instructions were to make three areas (blue for swamp, green for forest and yellow for sand), but otherwise no changes were made to the context. Adjustments in instructions and assignment were made on two areas: introduction of the context and whether emphasis is placed on either the workings of SimSketch or on the research question. The introduction of the context can have variable depth and elaboration. The teacher could, for example, only tell that snails can mutate to have different colors and that they are hunted by birds, or expand this by explaining the process of mutation of the DNA. This relates to the emphasis on SimSketch or the research question: spending more time on the explaining of underlying processes leaves less time for explaining the modeling tool and vice versa.

Though instructions and guiding questions are always available to the students in written text, these are static and mostly ignored by the students unless repeatedly mentioned that they have to be filled out. Oral questions are more personal and can be tweaked to fit the situation, but the teacher is not always available. One of the issues this study faces is the amount and type of support the teacher should and is able to give.

Scaffolding students' interaction with the program and reasoning about the experiment is the most important task of the teacher. Without giving answers away, the teacher can stimulate certain reasoning paths and dismiss others to help students reach higher understanding. But the teacher cannot be everywhere at once. Certain information and guidance should therefore be available to the students in a different way. Changes in instructions therefore also take place in the balancing of information and guidance that can be given in text, and information and guidance that can only be sufficiently given by the teacher.

Data collection

Students' conversations were recorded using voice recorders. The original intention was to combine students' conversations with the data logs from SimSketch (creation of the drawing, adding behaviors and the finished product), to see how their reasoning related to their drawing activities. However, getting the logs from the school computers to our own server proved to be difficult. Probably due to the heavy firewall settings of the school network, all initial attempts resulted in incomplete logs. To circumvent this, the logs of the final test were saved locally. These are the only complete logs.

Analysis

Students' conversations were transcribed and analyzed using part of the method for assessing reasoning complexity used by Hogan, Nastasi, & Pressley (1999). They found that the thinking of students who are equally inexperienced with a subject can differ greatly in depth and generativity. Reasoning complexity is therefore used to gauge the quality of students' learning, which focuses on their ability to explain and elaborate on their understandings, rather than on comparing their knowledge to that of experts. This method therefore discerns different levels of reasoning without judgment on right or wrong answers.

Though this does not show students' understanding of the subject of modeling, it does show how the process of modeling affects their reasoning both in number of expressions and in quality. Since the method is not specifically designed for a particular subject it was used without modifications and will be suitable for subsequent studies on SimSketch with a different modeling context, which would allow for direct comparison between studies.

The parts of the conversation where students discussed the assignment were selected and scored using the reasoning complexity rubric (see appendix A). This rubric gives a score on six complementing components, each having five levels (zero to four) for increasing complexity of reasoning. These are:

- Generativity: The number of subtopics within the discussion. Low scores are given for observations and generalizations; high scores are given for own ideas and assertions.
- Elaboration: The amount of detail given to the subtopics. Higher scores are given for more detail.
- Justification: The amount of evidence-based or inference-based support for an idea or assertion. Higher scores are given for more justifications per idea.

- Explanation: The mechanisms that are put forward to explain a phenomenon. Lower scores are awarded for single mechanisms, higher scores are given for multiple or chained mechanisms.
- Logical coherence: Judged by the soundness of explanations or justifications of a phenomenon. Low scores are given for nonsensical or vague connections; high scores are given for solid and coherent connections.
- Synthesis: Judged on the way different views are handled. Low scores a given to unresolved conflicting ideas, higher scores for supported rejection of one of the ideas, or combining ideas in to one, more complex idea.

Scoring scientific reasoning as such allowed us to compare different versions of SimSketch and the assignment throughout the iterations and see what elements stimulate or inhibit students expressing higher-level reasoning. Through four iterations, SimSketch and the assignment were changed to reflect these findings.

These findings and other notable discussions and events were noted and combined into recommendations for teachers and curriculum designers for using and constructing models in the classroom.

Results and discussion

For this study, SimSketch was renewed. The basic idea of SimSketch 1.0 was maintained: the newer versions of SimSketch are all still a drawing-based modeling tool in which behaviors can be dragged onto objects. The user interface and options, however, were completely revised. This segment will discuss the changes made to SimSketch, the teacher's instructions and the written assignment in chronological order. For each iteration the state of SimSketch during testing is described, along with the results of the analysis of students' conversations and how these results are incorporated in a new version of SimSketch, instructions and assignment.

First test

The redesign from the old version of SimSketch to the version of SimSketch used during this study focused on ease of use and therefore rearranged the whole user interface. Instead of having the drawing tools on the left and the behavior tools on the right (see figure 2), different modes were created. The buttons at the top of the screen corresponded to these modes: drawing, selecting, behavior and simulating (see figure 3). In drawing mode, the user has access to the pencil, eraser and object selection tool. When objects are selected, they can be moved and changed in size. In selecting mode the drawing strokes that should be considered as one object by the program can be selected by drawing a circle around them. Different objects are represented with different colors in this mode (see figure 3B: the top four lines will be considered one object, while the bottom four will be considered as separate lines by the program). In behavior mode, each behavior is represented by an icon that can be dragged onto an object. In the first version these behaviors are:

Movement
Adjustable speed and rotation angle.

Division
Adjustable division speed per minute.

Division with mutation
Set the attribute that is to be mutated, set how much the mutated offspring should differ from the parent and adjust division speed per minute.

Factory
Adjustable number of objects that should be generated and waiting time after generating an object.

Hunting
Set the prey; adjust the object's speed when trying to catch prey and the waiting time after catching a prey.

Fleeing
Set a predator; adjust the distance to take flight and speed of the object while fleeing.

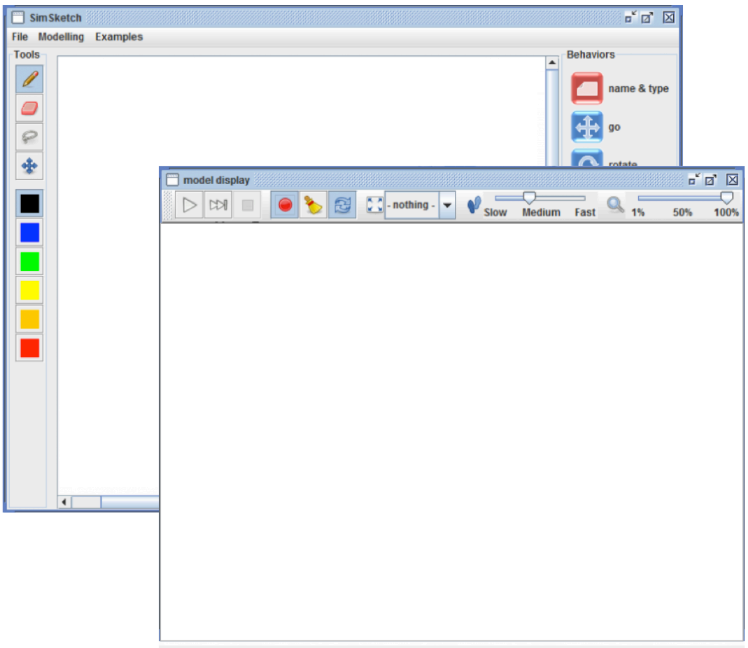

Figure 2: Overview SimSketch version from before this study. Left: modeling, right: simulating. In modeling mode all drawing tools are on the left and all behaviors are on the right. Simulation mode has buttons to play and pause the simulation, show the path the objects have traveled, slow down or speed up the simulation and zoom in and out. [from http://modeldrawing.eu/our-software/simsketch/]

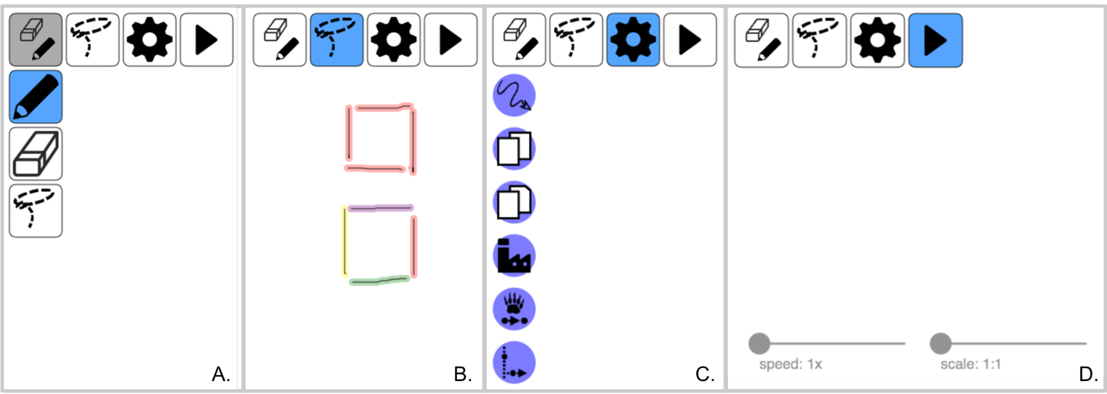

Figure 3: overview of first new version of SimSketch. A: drawing mode; B: Selecting mode; C: Behavior mode; D: Simulation mode.

Four students from the first grade of HAVO/VWO worked with this version of SimSketch, which was accessible online. The working of SimSketch was explained according to a different example than the assignment (in this case foxes hunting rabbits) and a brief explanation of heredity and mutation was given. The assignment was explained orally and given in print (see appendix B for the Dutch original and a translation of the assignment to English). This printed assignment also had some guiding questions, but none of the students filled in the paper. This version of the assignment had three areas: forest, sand and swamp.

The students in this first test spend most of their time trying to figure out how SimSketch worked, which left them with less time to spend on scientific reasoning. The analysis of students' conversations (see figure 4) shows that there were on average per couple 11 instances of scientific reasoning (22 total), of which the majority was on the lowest level of complexity.

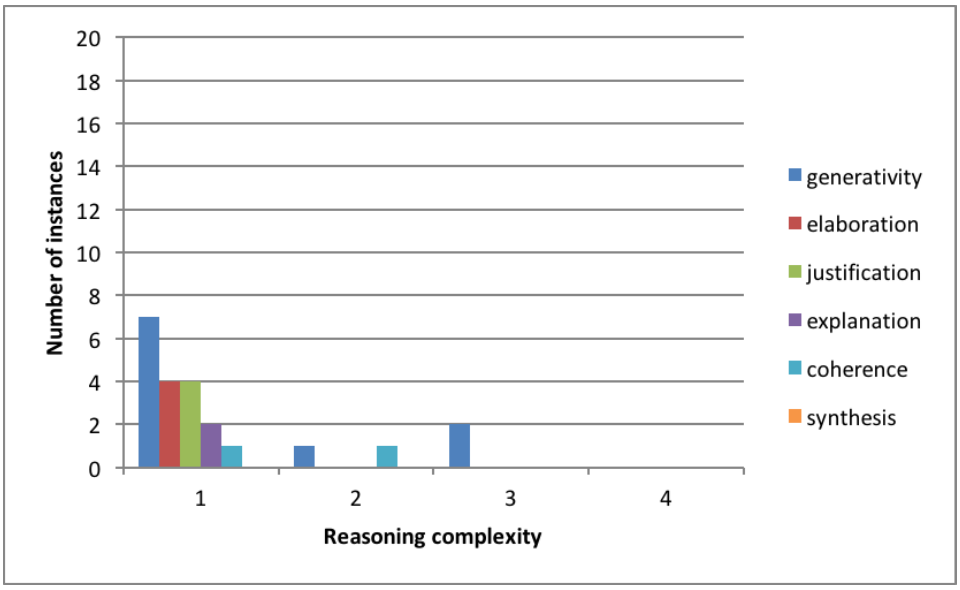

Figure 4: Overview of analysis of conversations of two couples of grade 1 HAVO/VWO students while working with SimSketch (first new version).

The two segments that scored highest were in the conversation of the same couple. All quotes from students are translated from Dutch to English. The first segment shows hypothesis building and explanation of the hypothesis supported by the teacher.

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.

And later in the conversation:

T: What do you think will happen with the snails in that area? Those that live on that bit?
S: Well, they get eaten a lot.
T: Why?
S: Because there are quite a lot, on a small area.
T: What is the difference with the snails that live over there?
S: Those get eaten even more because that is open field. It is a desert. Or sand.

This shows two things: students during this test did not engage in higher level reasoning without stimulation by the teacher and students had difficulty understanding the differences between model and reality. Ideally, some time would be spent discussing the various properties of the modeling tool, its limitations and its strengths, but this would detract time and attention from the modeling itself. It was therefore decided that students having issues with understanding this would be supported individually when needed.

For the teacher, discussing the behavior of the birds was difficult. The birds hunted by sight, but this was implicit in the program and not adjustable by the students.

Second test

To stimulate higher level reasoning without direct influence by the teacher, the attainability of the assignment needed to become higher and the time spent on modeling should outweigh the time trying to figure out the tool. To accomplish this, both the tool and the assignment were made easier to work with. In SimSketch, this mostly meant changes to enhance user friendliness: clicking an object to set characteristics would in all new version of SimSketch bring a menu on the right in which the user could set the type, name and value of a characteristic. In this version, clicking an object brings up a small screen in which the name can be typed and the color selected from a list. When attributing the hunting behavior to an object, the prey can now be selected from a list of all available object names, instead of having to type it.

To make students aware of the different ways the birds could hunt and make discussion of different hunting methods possible, the birds' hunting behavior was made a variable. Students can choose if the bird should hunt by distance to the prey, by sight, by distance and sight or randomly. By having to make this choice, students are stimulated to think about the implications of the different hunting behaviors. This change also allows teachers to reference the birds hunting behavior during discussions.

To limit distractions and uncertainty for the students, we took another look at the available behaviors. The flight behavior was not essential for building a working model and was therefore removed from SimSketch.

It was also apparent that the three areas left too much room for error: the colors of the areas were too close together, making it difficult to see different colored populations arising. To make the different population more visible for the students, from here on out the assignment stated two areas of contrasting color: red to represent clay and green for forest.

During this test, six students from the first grade of HAVO/VWO worked with SimSketch, which was available online. A brief explanation of heredity and mutation was given and SimSketch was explained by drawing part of the snail and birds model and giving the objects different behaviors. The teacher showed the students the different hunting behaviors without explaining the implications they could have on the snail population. The written assignment had an extra sentence explaining the effect of mutation on the snails and stated the colors of the two areas to prevent confusion.

During this test, the average number of instances of scientific reasoning per couple was higher than the number in the first test: here students showed an average of 13 instances of scientific reasoning (see figure 5). The level of reasoning was also higher.

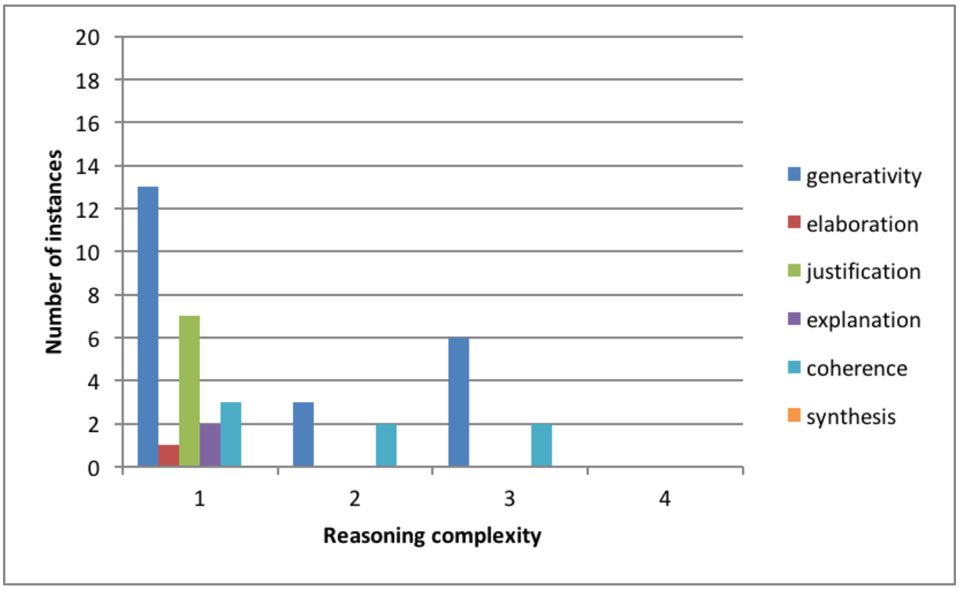

Figure 5: Overview of analysis of conversations of three couples of grade 1 HAVO/VWO students while working with SimSketch (second new version).

Making the hunting behavior of the birds explicit helped during discussion:

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.

In the conversation of another couple we see that de appearance of the two populations is noted, though the reason why the two populations come to be is not entirely clear to the students.

T: But do you also see a difference between this area and that area?
S1: They have like a bit more greener, green blue kind of. And here red, orange, yellow, pink, purple.
T: How do you think that came to be?
S1: Err… That is because- Those go to this area and the others go to that area, because they feel more at home or something?
T: Why do they feel more at home there?
S2: Because otherwise they are bullied.

Though none of the students came to the conclusion that two populations of different colored snails emerge because of the hunting behavior of the birds, reasoning about the snails' colors and the possible influences on them was taking place.

Third test

For this version of SimSketch, some changes were made to further improve the ease of use. Most notable of these was removing the scaling option. Students were able to zoom out in simulation mode, but this interfered with modeling because this meant there was a white area around the two colored areas. This gave the snails room to spread there, meaning that birds hunting by sight would pick off only the snails in the white area because they had the highest contrast. Removing this function had no negative effects on modeling.

There were also some basic statistics tools added to help students make sense of their observations. This included the number of objects with a certain name and the average contrast between objects and background.

The day the third test was done we had access to two third grade HAVO classes. To make the most use of this opportunity, we decided to test the influence of the way SimSketch and the assignment were introduced on the way that students interacted with the program.

For both tests, six students worked in pairs. Suspecting that the schools computers prevented the logs from being recorded, we took three of our own laptops to the school. Because each couple therefore had access to only one computer, the assignment was adapted to have students work in pairs from the start.

In the first group, the emphasis was placed on the research question. Students were asked early on what they thought was going to happen with the colors of the snails, while explaining the workings of SimSketch was put on second place. In the second group emphasis was placed on explaining SimSketch. The research question was only written down in the assignment and not repeated during the initial instructions. The impact this had on the students' reasoning is shown in figure 6 and figure 7. It should be noted here that students in the first group had slightly less time to work on the assignment, due to trouble with classroom reservations.

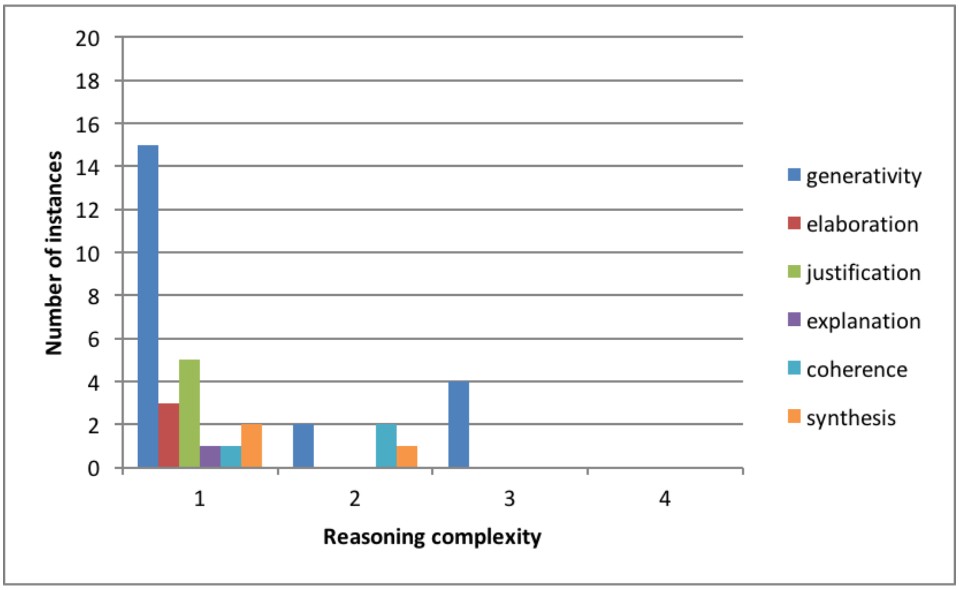

Figure 6: Overview of analysis of conversations of three couples of grade 3 HAVO students while working with SimSketch (third new version) who received instructions with the emphasis on the research question.

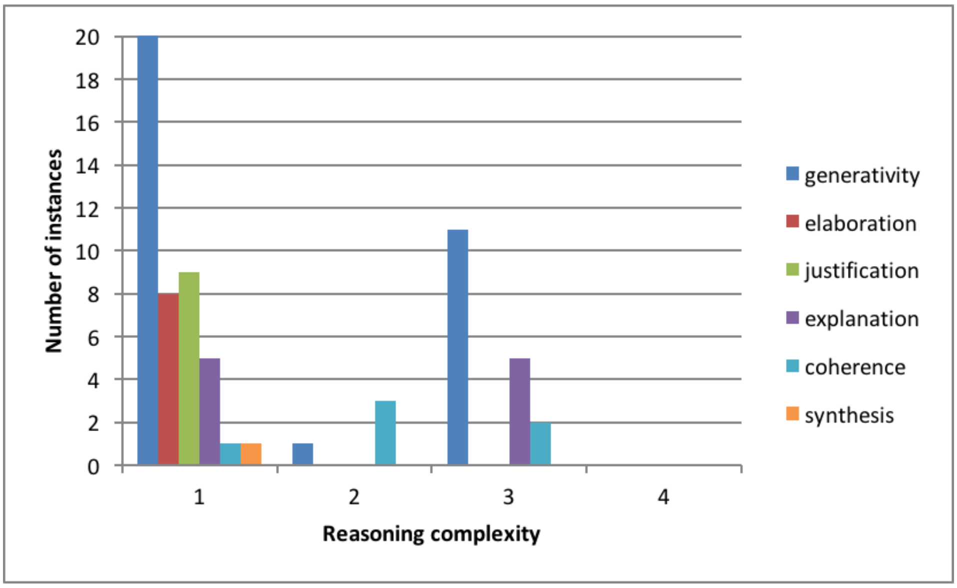

Figure 7: Overview of analysis of conversations of three couples of grade 3 HAVO students while working with SimSketch (third new version) who received instructions with the emphasis on the workings of SimSketch.

It is clearly visible that students in the second group spoke more about the modeling process in reasoning terms than the first group (a total of 87 versus a total of 36). This places the average number of reasoning instances per couple in the first group around the same level as the first two tests, while the average of the second group is more than twice as high. Almost half of these utterances fall in the level 1 generativity category, meaning they are simple observations. There are also, however, noticeably more higher-level reasoning patterns visible. For the first time observed during this study, students also showed higher-level reasoning while discussing amongst themselves, without direct stimulation from the teacher.

The written assignment was filled out by most students in the first group, but by none in the second. Two examples of filled out assignments (both the Dutch original as well as an English translation) can be found in appendix C. Filling in the assignment seems to be related to the amount of pressure the teacher puts on it, as it was emphasized in the first test, but not in the second that it needed to be filled in. Filling in the assignment did not seem to have a direct influence on the students' level of reasoning complexity.

A comparison between the results of the two groups suggests that the explanation of the modeling tool is most important for students working with the program for the first time. Though students in the second group did spend some time wondering what the goal of the assignment was, they also spend a lot of time talking about what happened in their simulations. Even more, one of the couples came to the conclusion that birds eating more snails of a contrasting color results in two snail groups that have a color close to the background color.

One example of students showing higher level reasoning without prompting by the teacher, though not directly related to the snails' colors is shown below. The students observe in the simulation that all their snails (which they called Esmeralda) and birds (which they called George) are dead and explain why that would have happened. They also elaborate on what would have happened if the birds had died out first.

S1: What happened?
All of a sudden they were dead.
Oh whatever, we did well.
S2: We kept them alive as long as possible.
Probably Esmeralda died first and then George didn't have any food left.
S1: Yes, because when George dies first then-
S2: That doesn't matter-
S1: That doesn't matter-
S2: Because Esmeralda stays alive.

One couple came to the right conclusion when prompted by the teacher and then went on to elaborate and explain their findings.

T: And if it would hunt by 'this is the snail I can see the best'?
What do you think would happen then?
S1: Then it will…
S2: Then it will-
S1: Then it will hunt by color.
S2: Yes, I think so too.
Then it will hunt… On red it will hunt the green things and on green the red things.
I think.
S1: Exactly.
T: So what would you see happen then?
What kind of snails would you get here and-
S2: Then you would get a lot of green snails here and here a lot of red snails.

After the teacher left, the student explained further:

S2: I think that if the birds… Imagine there is a snail that has the same color red as this, that the bird can't hunt it because is can't see the snail. Hardly.

Also notable is that multiple students in the second group spoke of 'finishing the game' (Dutch: 'uitgespeeld'), while none of the students in the first group did. This could mean that students in the second group viewed SimSketch more as an environment to play in than as a school assignment, which could have influenced the way they interacted with the tool. This, in turn, could have contributed to the higher number of reasoning instances in the second group.

Multiple students seemed to be confused by the utility of the 'factory' behavior and had to ask the teacher what is was and what it did during modeling. The simple statistics tools seamed to confuse students more than help them.

Fourth test

The factory function was replaced by the duplication function, which was placed in object selection mode.

The statistics tools were expanded to enable students to select variables to show a graph of. This allowed them to see the number of objects in a category, the contrast between a category of objects and their background, and the number of objects in each area.

In the final test, with six grade 2 HAVO students, the influence of the introduction can also be seen. Here, the teacher first introduced the assignment and refreshed or explained relevant knowledge, emphasizing that students should follow the written instructions (see appendix D for the original in Dutch and the English translation). The teacher then explained the different modes and behaviors in SimSketch by drawing part of the assignment. An overview of the version of SimSketch used during this test can be seen in figure 8 (also compare to figure 3).

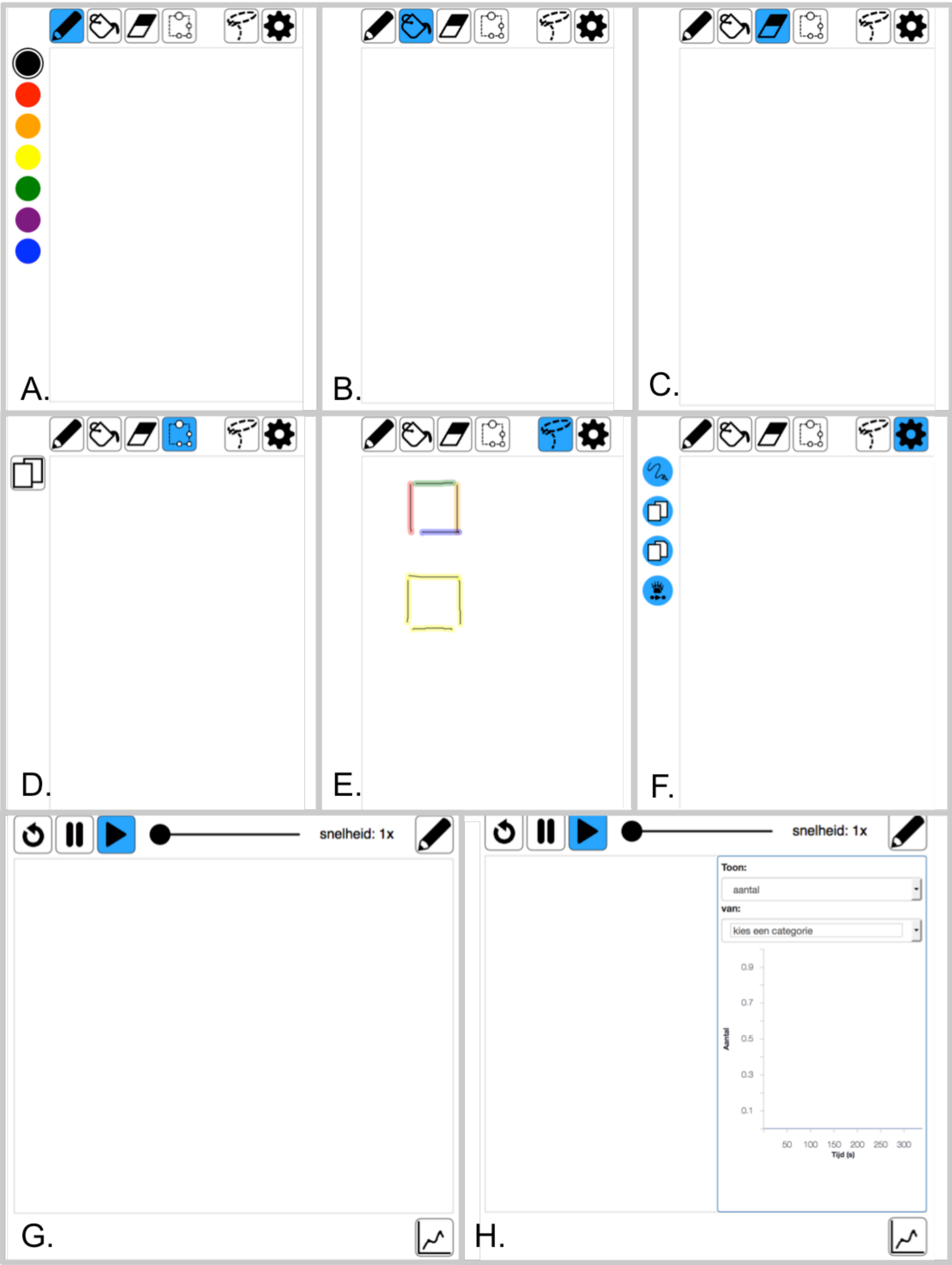

Figure 8: overview final version of SimSketch. A: Drawing mode, with selectable colors on the left. B: Filling tool. C: Eraser tool. D: Modification tool, with copy tool on the left. E: Object selection mode, with different colors indicating different objects. F: Behavior mode, with icons of the four behaviors on the left. G: Simulation mode with replay, pause and play buttons, speed adjustment slider, pencil button to go back to behavior mode and graph button in the lower right. H: clicking the graph button brings up a tool in which can be selected of what category of objects a graph is shown of the number, contrast with background or location of this category.

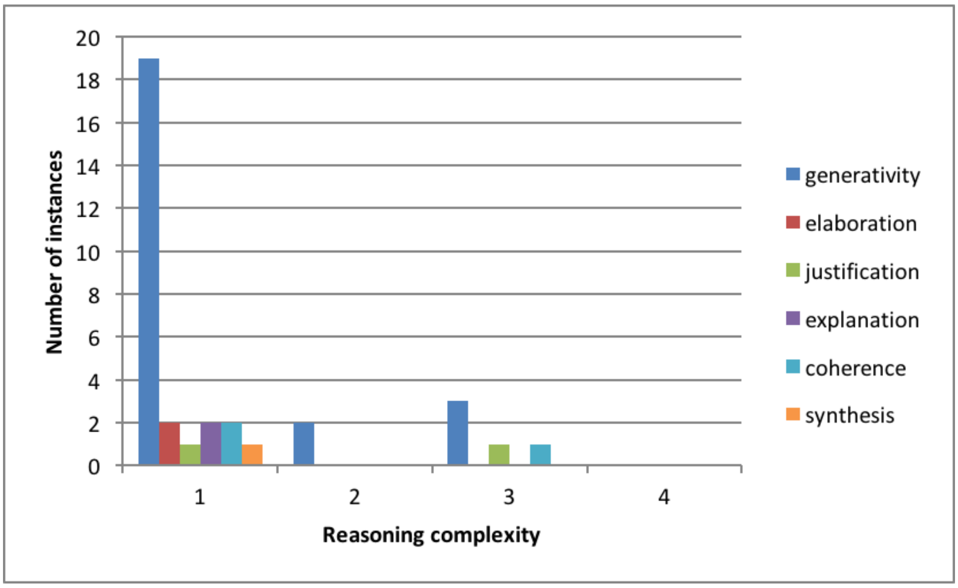

Figure 9: Overview of analysis of conversations of three couples of grade 2 HAVO students while working with SimSketch (final new version).

Relatively few instances of scientific reasoning were recorded (see figure 9). In comparison with the first and third grade students, these students seemed most hesitant to start working on the assignment. This could be connected to the way students accessed SimSketch: during previous tests SimSketch was available online, while in this test students accessed the program via a USB drive. This has an effect on the students' first impression of SimSketch. Instead of a well-known way to play games (in a browser), students had to click through multiple folders to access this unknown program.

This way of accessing SimSketch was necessary to ensure that logs were recorded during this test. Log files were saved locally, on the USB drive, circumventing the schools' network settings. While the analysis of students' conversations show the level of their reasoning, the log files give insight into the structure of their reasoning while working with SimSketch. The log files show the steps students take when creating their model: most students first draw the two areas, the snails and the birds, assign behaviors and then go back and forth between playing the simulation and adjusting the behaviors. Some students initially forgot to select the lines constituting one object, but amended this after playing the simulation for the first time. Notable was that some students used all behaviors on all objects. Apparently it was not clear that not all behaviors should be used on all objects. Most students drew the snails in different colors. Though this should have no effect on the outcome of the simulation, it is notable that these students apparently misunderstood the difference between snails *becoming* different colors and snails *being* different colors. There also seemed to be some confusion between the 'division' and 'division with mutation' icon. Some students used both on the same object.

The higher level reasoning that was recorded can mostly be attributed to students discussing what they should write down on the assignment sheet. Only one couple came close to the right conclusion, discussing at the start of the lesson:

S1: What do you think happens to the color of the snails' shells?
That it- if it is hunted, then I think that they get a bit darker.
S2: Yes, like the shrubs. As camouflage.

Observing halfway through (though mixing up names of colors):

S2: If they are in the blue area they become blue.

But concluding:

S1: First it was blue, but then it became more green.
S2: And then it became totally green and then-
S1: Now it becomes dark black.
S2: Then red.
S1: Where did you see red?
S2: Here.
S1: And then, see, yes red.
S2: And then pink. It becomes lighter, this color.
S1: Conclusion?
S2: The colors are getting lighter.

This shows that a promising hypothesis does not always lead to the expected conclusions. The log files show that the hunting behavior of the birds was not set on hunting by sight (see figure 10), resulting in a different change in the snails' colors. The teacher's help or personal feedback from the program would have been needed to get the students back on the right track.

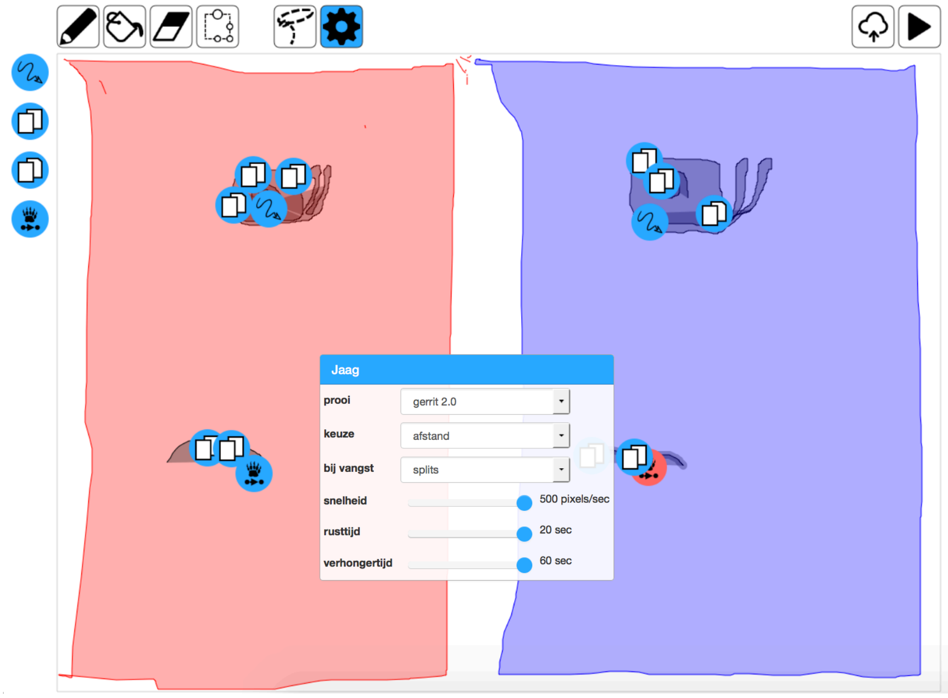

Figure 10: Example of student's modeling. The two snails have multiple division behaviors. The two birds hunt by distance.

This was the only test in which all students filled out the written assignment (see appendix E for examples). The assignment did help to structure some students' thinking, allowing them to make a reviewable hypothesis early on. The amount of detail, both in the hypothesis as well as in the final conclusions, is poor. This could be enhanced by stimulation by the teacher or by spending some dedicated time discussing hypothesis building and conclusion writing. During these tests, however, this was not the primary goal and the limited time of the lesson left little room to spend more attention to this.

Summary and Conclusions

The first step to make successfully finishing the assignment more attainable for students is simplifying. For the assignment this meant going from three areas (forest, sand and swamp) to two with contrasting colors (forest and clay), which made the difference between the two populations easier to observe. Simplification was also applied to the modeling environment: those functions that were not strictly necessary for building a successful model were removed. For students who work with SimSketch multiple times it could be beneficial to have some redundant functions, to make them reason about the things they really need and see how multiple functions influence the outcome of their model. The students in this study, however, all experienced working with a drawing-based modeling tool for the first time. To make the attainability of the assignment for these students higher, the decision was made to remove the ‘flee’ functions, and later integrate the ‘factory’ function into the object selection tool. This made all behaviors in behavior mode essential for building a working model, thus removing distraction and uncertainties for the students. This allowed them to spend more time building models, with more certainty of going in the right direction.

Secondly, students need to be able to manipulate key variables of the model to fully comprehend the processes in the simulation. In this case that meant going from birds automatically and implicitly hunting by sight to having students set the way the birds hunt. Though this increases the chance of students setting a hunting behavior that does not give the desired result, it does allow for discussion of the influence of different hunting behaviors on the snails and when supported properly by a teacher, allows for students to have a deeper understanding of the processes happening in their model.

The first time students work with a drawing-based modeling tool they will need a lot of support. This is apparent in the hesitance many students showed and the amount of questions they asked the teacher, both about the working of the program and to give feedback on their progress. A written assignment can be used to structure reasoning processes, but feedback and support from the teacher using scaffolding practices is essential. Students often observe things happening in their model without giving reasons for why something would happen. Teachers can stimulate students’ scientific reasoning by asking these scaffolding ‘why’ questions.

Finally, the setting of the introduction is important. Using SimSketch in a browser seemed to stimulate students’ playful behavior, while students using SimSketch from a USB drive seemed to be more hesitant. A playful attitude and not being scared to make mistakes are the best way to develop scientific reasoning skills with SimSketch.

Recommendations for teachers and curriculum designers

Some students successfully set up models within thirty minutes of first encountering a drawing-based modeling tool. This suggests that with sufficient support and time, most –if not all– students will be able to successfully set up models using a drawing-based modeling tool.

For the first encounter with this new medium it is most important to explain the basics of the tool. This can take away some of the insecurities of the students and enables them to play around with the tool without having to consult a teacher. This playing around, without directly worrying about right or wrong actions, is important for students to form their own understanding of the tool and the interactions between objects. Explaining the different functions (drawing, selecting objects, assigning behaviors, running simulation) of the tool in the same order you would use them in the assignment can help students place the functions in a broader frame, instead of seeing them as separate units.

Use scaffolding while students work on the assignment to keep them on track, without giving away answers. Students will often talk about their observations, but reasoning about the reasons why they happen can be lacking. Though assignments can have guiding questions, these can be misinterpreted (e.g. Why do you get two different colors of snails? Because the snails mutate.), while teachers' questions are more interactive and can go more in depth. Teachers can, for example, ask questions using the same terms and names the student uses and ask for more support behind an assumption or idea. Interaction with the teacher can also help to timely redirect students' reasoning to a promising path by using personalized questions and hints.

It is also recommended to pay attention to the limits of the modeling tool and the models that can be made with it. By discussing with students what parts of the model are realistic and which are not, what could be added to make it more realistic and which simplifications are necessary, students can gain a deeper understanding of models and how they are used. By experiencing different subjects through models and discussing the link between model and reality, this could eventually lead to understanding how models are used in science.

Understanding of the subject of modeling is part of the reasoning process. During this study, it was unclear if students understood that the assignment was about evolution. For implementation in the classroom, the outcome of the students' models and their meaning should be discussed classically to ensure comprehension by all students.

Limitations and further research

Because of limited time and resources, a maximum of six students were included per test. This did allow for a relatively quick turnover time between iterations. Though using more students would have given a better overview of the student population, using small samples of students allowed for a qualitative, in depth approach.

The selection of students was random in the first and second grade classes, but based on which students could miss a biology class according to their teacher for the third grade students. This was the case because the third grade students had many exams near the end of the school year. The students selected by the teacher were either those that would in his opinion feel no negative effects from missing a class, or feel no positive effects from following the class. This resulted in a mixed group of high scoring and low scoring students. Though perhaps not most representative of the whole class, these students did show that they could work together and stimulate each other to produce a simulation. This suggests that students who score closer to the average would be able to do so as well.

For the first three tests, SimSketch was run from a website, while in the fourth it was run from a USB drive to allow local saving of log files. This could influence the way students viewed the modeling tool: during the first iterations some students spoke of SimSketch as a game, while in the last iteration none did. This could have contributed to students' unwillingness to 'play' with the program.

For further research it would be interesting to see how students interact and reason while using SimSketch during a series of lessons, instead of just one. More attention could be paid to understanding SimSketch before working on the main assignment, using real life contexts and to the limitations of the modeling tool in comparison with reality. By changing the behaviors inside the tool, SimSketch can be used for a variety of subjects.

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Appendix A: Reasoning complexity rubric

Criteria	*0*	*1*	*2*	*3*	*4*
Generativity	No observations or ideas	One to two observations or confirmed generalizations	Three or more observations or confirmed generalizations	One to two own conjectures, ideas, or assertions	Three or more own conjectures, ideas, or assertions
Elaboration	No elaboration	One to two elaborations of one idea	One to two elaborations of more than one idea	Three or more elaborations of one idea	Three or more elaborations of more than one idea
Justifications	No justifications	Single justification of one idea	Single justifications of more than one idea	Multiple justifications of one idea	Multiple justifications of more than one idea
Explanations	No explanations	Single mechanism of one phenomenon	Single mechanism of more than one phenomenon	Multiple or chained mechanisms of one phenomenon	Multiple or chained mechanisms of more than one phenomenon
Logical coherence	No logical connections invoked	Nonsensical connections made	Vague, underspecified connections making superficial sense	Clear and reasonable connections, but lack support	Solid, principled, and coherent connections
Synthesis	No contrasting views emerged	Two counter ideas coexist separately and unresolved	Two counter ideas explicitly combined without deeper conceptual resolution	One counter idea prevails through support given for it	Two or more counter ideas synthesized into a more complex, coherent idea

Appendix B: First version of written assignment

Er zijn drie gebieden: bos, zand en moeras. In deze gebieden komt een slakkensoort voor. De kleur van hun huisjes is erfelijk, maar soms komen mutaties voor. De slakken worden gegeten door vogels.

Wat moet je allemaal tekenen om hiervan een goed model te kunnen maken?

Wat denk je dat er gebeurt met de kleur van de huisjes van de slakken?

Teken nu eerst zelf de dingen die je nodig hebt in het model. Geef elk object het gedrag dat het nodig heeft. Speel je model af en laat het een tijdje lopen.

Wat gebeurt er met de kleur van de huisjes van de slakken in jouw model? Klopt dat met je antwoord hierboven?

Werk nu samen met je buurman of buurvrouw. Voeg de beste onderdelen van jullie modellen samen tot één model en overleg hoe jullie het model nog realistischer kunnen maken.

Wat is er veranderd ten opzichte van je eerste model?

There are three areas: forest, sand and swamp. In these areas lives a snail species. The color of their shells is hereditary, but sometimes mutations occur. The snails are eaten by birds.

What do you have to draw to make a good model of this?

What do you think will happen with the color of the snails' shells?

First draw the things you need for the model. Give each object the behavior it needs. Play your model and let it run for a while.

What happens with the colors of the snails' shells in your model? Does that fit with your previous answer?

Now work together with your neighbor. Combine the best parts of your models into one model and discus show you can make the model even more realistic.

What changed in comparison to your first model?

Appendix C: examples of answers on assignment from the third test (Dutch and translated answers)

Question	Dutch	English
What do you have to draw…?	Gebieden, slakken en vogels	Areas, snails and birds
What do you think will happen…?	Ik denk niet dat het totaal anders word maar dat de kleuren lichter worden ofzoiets.	I don't think it will be completely different but that the colors become lighter or something
What happens… in your model?	Ze worden soms lichter en soms donkerder. Ja dat klopt.	They become sometimes lighter and sometimes darker. Yes, it's right.
Further changes…?	De verhongertijd van de vogels anders gaan ze te snel dood.	The starvation time of the birds otherwise they die too soon.

Question	Dutch	English
What do you have to draw…?	Roofvogels, slakken, 2 grondsoorten	Birds, snails, 2 types of soil
What do you think will happen…?	De kleur wordt anders	The color becomes different
What happens… in your model?	Ze worden allemaal anders gekleurd	They become all different colored
Further changes…?	Snelheid, verhongertijd	Speed, starvation time

Appendix D: Final version of written assignment

Er zijn twee gebieden: bos (groen) en kleigrond (rood). In deze gebieden komt een slakkensoort voor met gekleurde huisjes. Door mutaties hebben de slakken soms een andere kleur huisje dan hun ouders. In het gebied leven ook vogels, die jagen op de slakken. De onderzoeksvraag is:

Wat gebeurt er met de kleur van de huisjes van de slakken in de twee gebieden?

1. Wat moet je allemaal tekenen om een goed model te kunnen maken?

2. Wat denk je dat er gebeurt met de kleur van de huisjes van de slakken?

Maak nu je model. Speel je model af en laat het een tijdje lopen. Pas het model aan als je na korte tijd alleen slakken of alleen vogels over houdt.

3. Wat gebeurt er met de kleur van de huisjes van de slakken in jouw model? Klopt dat met je antwoord hierboven?

Werk nu samen met je buurman of buurvrouw. Voeg de beste onderdelen van jullie modellen samen tot één model en overleg hoe jullie het model nog realistischer kunnen maken.

4. Schrijf op de achterkant wat je verder aanpast aan je model en hoe dat de kleur van de slakken beïnvloedt.

There are two areas: forest (green) and clay (red). In these areas lives a snail species with colored shells. Because of mutations the snails sometimes have a different color shell than their parents. In the area there are also birds, who hunt the snails. The research question is:

What happens with the colors of the snails' shells in the two areas?

1. What do you have to draw to make a good model?

2. What do you think will happen with the colors of the snails' shells?

Make your model. Play it and let it run for a while. Adjust your model if you have only snails or only birds after a short period of time.

3. What happens with the colors of the snails' shells in your model? Does that fit with your answer above?

Work together with your neighbor. Combine the best parts of your models into one model and discuss how you could make your model even more realistic.

4. Write on the back of this paper what changes you made further and how that influences the color of the snails.

Appendix E: examples of answers on assignment from the final test (Dutch and translated answers)

Question	Dutch	English
What do you have to draw…?	2 gebieden, slakjes, vogels	2 areas, snails, birds
What do you think will happen…?	Die veranderen. Dna van moeder + dna van vader → kleur verandert	They change. Dna of mother + dna of father → color changes
What happens… in your model?	Niks	Nothing
Further changes…?		(empty)

Question	Dutch	English
What do you have to draw…?	Een mooie slak, mooie achtergrond en mooie vogels tekenen	Draw a pretty snail, pretty background and pretty birds
What do you think will happen…?	Camoeflage met donkere kleuren omdat ze moet vluchten	Camouflage with darker colors because they have to flee
What happens… in your model?	Hij word groen bruin donker zwart	He becomes green brown dark black
Further changes…?	Conclusie: de kleuren worden steeds lichter	Conclusion: the colors become lighter and lighter