Using an iconic modelling tool to support the learning of genetics concepts

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Genetics is a difficult topic as it involves abstract concepts, which are not directly observable. Studies on using simulations to support the learning of genetics have largely been confined to the use of quantitative simulations to replace experimentation. This study describes the use of a new type of simulation built using an iconic modelling tool, WorldMaker (WM), that can (1) support multiple iconic visualisations of the simulated phenomena, (2) support the visualisation of instantaneous local changes as a simulation is executed as well as the time variation in global changes as the simulation unfolds, and (3) allow the user to examine and modify all of the rules governing the behaviour of the simulations. This study reveals that students' exploration of genetic phenomena using simulations built in WM elicits theorising from them that exposes their prior misconceptions as well as stimulates further exploration and co-construction of genetic understanding that is closer to the scientific view. It helps students to understand operationally difficult concepts like genotypes and phenotypes, as well as to understand genetic ratio as a deterministic value derived from inheritance events that are probabilistic and random in nature.

Key words: Conceptual change, Genetics, Modelling, Simulations.

Introduction

Genetics is widely recognised as a conceptual foundation for the understanding of evolution and thus of biology itself (Deadman and Kelly, 1978; Wood-Robinson, 1994). It is therefore not surprising that genetics is included in most secondary school biology curricula around the world. However, research has also found genetics to be an area where many students encountered conceptual difficulties that are difficult to overcome.

Difficulties in the learning of genetics concepts

One major source of difficulty relates to the nature of inheritance. While most people have vague ideas that parents are the source of inherited characteristics, they do not have clear ideas about the nature and mechanism of inheritance. Kargbo, Hobbs, and Erikson (1980) documented three kinds of students' conceptions in this area. One popular belief was that one of the parents contributes the genes for some characteristics, while other features come from the other parent. Another belief related to a kind of gender inheritance of characteristics, is that offspring tend to inherit characteristics coming from the parent of the same gender. A third common belief centres around the imbalance of influence according to the gender of the parent: the belief that females would contribute more than males or vice versa. These kinds of misconceptions were also found by Clough and Wood-Robinson (1985).

Another area of difficulty is the distinction between inherited and non-inherited change in organisms (Brumby, 1979). Kargbo et al (1980) found a widespread belief amongst six to 14 year-old Canadian students that acquired characteristics were in fact inherited. About half of their samples thought that a lame puppy would be born to a dog that limped as a result of an accident. Similar findings were also reported by Clough and Wood-Robinson (1985), who investigated the understanding of inheritance held by 84 secondary school students. They found that the idea of the passage of time having an influence on phenotypic change was a compelling one for many students.

In another study, Lawson (1988) asked 131 Grade 7 students aged 12 to 13 to predict the offspring's skin colour, hair colour and finger length. Responses from the students revealed that they tended to invoke the naïve concepts more often when the changes were gradual. Supporting evidences were also found in a related study by Ramorogo and Wood-Robinson (1996). They found that when the idea of time was introduced, most students believed that the acquired characteristics would become inherited after several generations.

Genetic ratio is another difficult concept for students. According to Longden (1982), students generally understood the genetic ratio as a fixed number and routinely used the Punnett squares to solve genetics problems. Following this, Kinnear (1983) pointed out that students perceived genetic ratios as a deterministic parameter rather than a probabilistic one. This inability to understand the probabilistic nature of genetic phenomena is another major obstacle to the learning of genetics concepts.

In addition to finding many of the genetics concepts difficult, research also reveals that students found much of the associated terminology confusing and difficult to distinguish. Longden

(1982), Stewart (1982, 1983), Tolman (1982) and Pashley (1994) found that students had difficulties in explaining some basic terms in genetics such as allele, gene, chromosome, chromatid and gamete. Further, they did not understand the relationship between these concepts.

It is hypothesised here that underlying the many conceptual difficulties encountered by students are three fundamental obstacles. Firstly, understanding of the genetic theories require the learner to relate the propagation of observable genetic traits to the abstract, non-observable concept of genetic composition in chromosomes, and to be able to visualise multiple genetic compositions to be mapped to the same observable trait because of the existence of dominant and recessive alleles. Using the technical terminology in genetics, this difficulty relates to the fact that there are multiple genotypes associated with the same phenotype.

A second and related obstacle is that of understanding a genetic theory as a formal system that describes all the necessary factors and conditions that prescribes and predicts the behaviour of the system. A third obstacle is with understanding complexity, in appreciating how complex phenomena can arise from simple interactions and how deterministic patterns and trends can arise from random events.

Use of simulations in the teaching of genetics

Studies into ways to improve students' conceptual understanding in genetics have centred on the design of activities that help students to make their ideas explicit, and which encourage them to explore their ideas more deeply. Okebukola (1990) employed concept mapping activities to foster conceptual change. Data from this study showed that the experimental group, which engaged in concept-mapping activities, outperformed the control group. Soyibo (1991) also showed that concept mapping significantly improved Grade 10 students' (aged 15 to 16 years) achievement in both genetics and ecology. More recently, Pashley (1994) used a chromosome model as a conceptual tool to resolve students' misconceptions.

Another approach was to use computer-based simulations to confront students' alternative conceptions. Kinnear (1983, 1986) and Browning and Lehman (1988) both reported that the use of computer simulations contributed to students' conceptual development through helping to identify and confront their misconceptions. These studies focused on the exploratory aspect of using simulations as an alternative to experimentation, which is comparatively difficult to conduct in school laboratory situations. However, similar to the case of experiments in science education, the use of computer-simulated experiments does not necessarily lead to the desired understanding of scientific principles as any phenomenon may be interpreted in multiple ways. In the study reported in this paper, simulation and modelling activities were used to explore their pedagogical impact on students with various levels of biological knowledge.

Methods

Using an iconic modelling tool to support conceptualisation and understanding of Mendelian genetics as a formal system

The study reported in this paper was conducted with senior secondary school students using an iconic modelling tool, the Worldmaker (hereafter referred to as WM) (Law, 1998; Law et al, 2000). The modelling environment in WM is based around a 'World' configured as a grid system. Each cell in the grid may have up to two entities located in it: a foreground object and a background object, which may interact together or separately. In this environment, users can build models through defining entities (objects and backgrounds) and events (rules of local interactions between co-located entities in the 'world'). WM further provides a graphing tool that captures the real-time variation of the total number of selected entities while the model is running, thus supporting the visualisation of phenomena at both the iconic instantaneous level and as a global variation over time.

Supporting multiple visual representations of trait (genetic) theories

WM can be used to construct models (simulations) of genetic theories that are easily explorable by learners. WM thus acts as a form of modelling clay for thinking and learning (Ogborn, 1999) topics and concepts in genetics. As mentioned earlier, a major source of difficulty in visualising the propagation of genetic traits relates to the fact that there are often multiple genotypes associated with the same phenotype. In WM, the iconic image used to represent an entity is totally independent of the rules of interactions of the entities. Thus, we can use different icons to represent the same genotype. Figure 1 a, b and c are three icons representing three genotypes of rabbit coat colours. Figures 1b and 1c are both brown, and are thus phenotypically identical. The letter H in Figure1b is used to indicate that this genotype is in fact a heterozygote while the letter D in Figure 1c indicates that it is a homozygote.

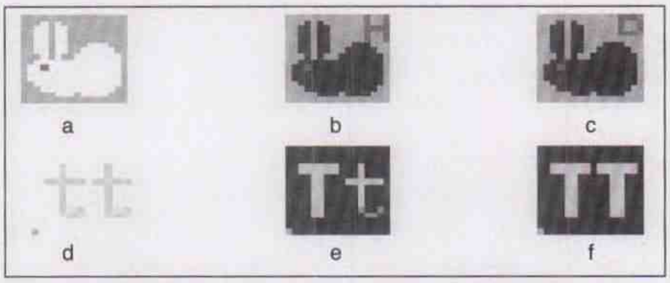

Figure 1 a, b, c are icons in Worldmaker, highlighting the phenotypic variations for the three genotypes of rabbit coat colour, while d, e and f are icons for their respective genotypic representations highlighting the allelic composition.

Creating a model of rabbit reproduction

Using WM, it is very easy to create a model of rabbit reproduction (hereafter referred to as 'reproduction world') by defining the possible offspring genotypes or phenotypes and the respective probability for each. For the purpose of the study being reported, the reproduction world created the parent genotypes as background entities and offspring genotypes as foreground entities. Two reproduction worlds were used. The first one used phenotypic iconic representations with the entities as shown in Figure 2.

The behaviour of any simulation created in WM depends entirely on the rules of interaction that have been defined for each of the defined entities in the world. Figure 3 shows an annotated screen capture for the rule definition panel, which can be used to inspect or define the rules of interaction that governs the behaviour of the entities. Different simulations can then be created by placing different entities on the world grid.

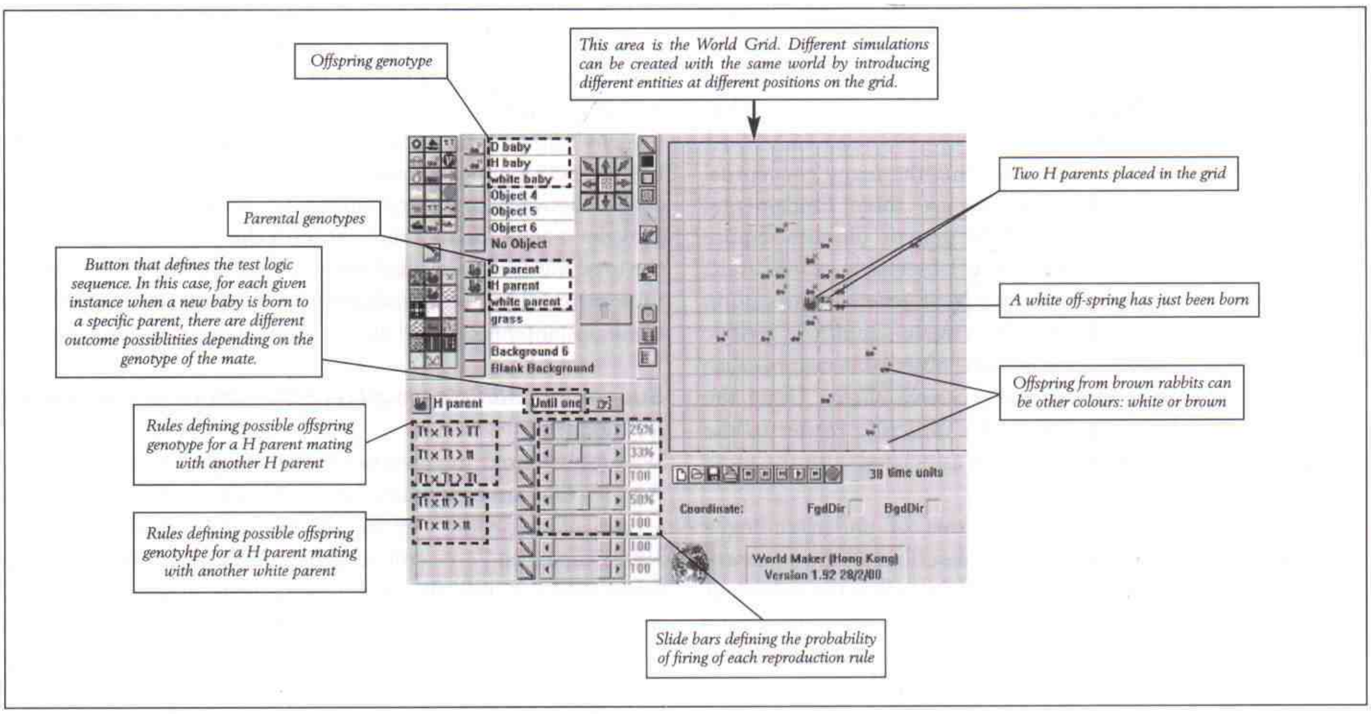

Figure 2 *Diagram showing the screen layout of WM when a simulation created with the reproduction world is in execution*

In WM, the specific iconic image associated with an entity can be changed without affecting the nature of the model at all. Therefore, the reproduction world would operate in exactly the same way if the icons for the parents and the offspring were changed. In this study, two sets of icons are used to create the reproduction world, resulting in two versions of the world: to be referred to as phenotypic reproduction world and genotypic reproduction world respectively. The icons used in each of these two versions are given in Figure 4.

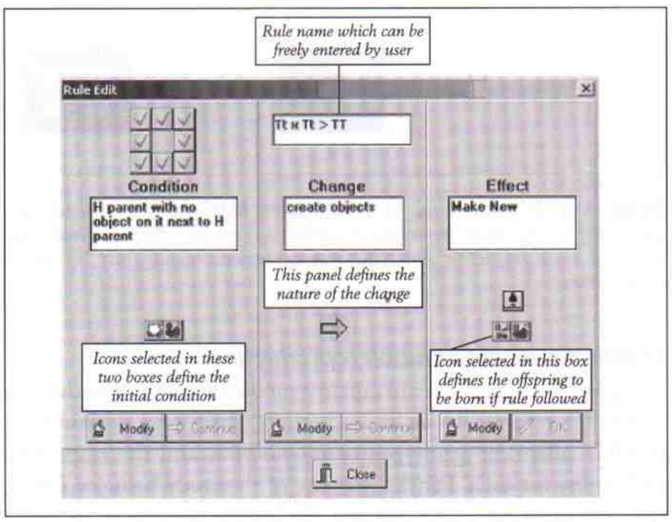

Figure 3 *The rule definition panel for defining or inspecting the rules governing the behaviour of different entities.*

A statistical tool to provide information on global change over time

In addition to observing rabbit babies being born and jumping around as time moves on, there is a statistical function available that allows the user to see a graph of the total population of defined entities over time. This feature offers a unique opportunity for the user to visualise phenomena at two levels: the local, often probabilistic, interaction level and the global, often deterministic

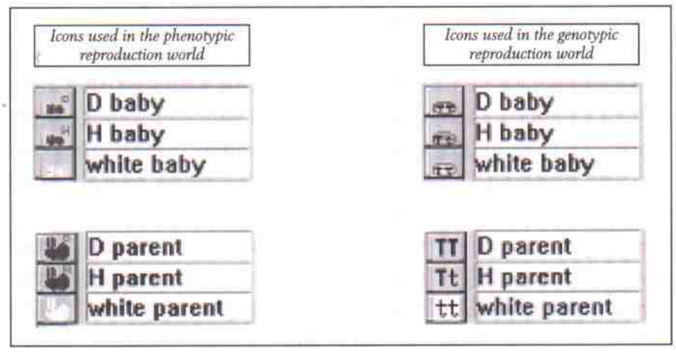

Figure 4 *The two sets of icons used in the two versions of rabbit reproduction world used in this study.*

behavioural trend level. WM can thus bolster learning by helping the learner to visualise the same phenomenon using different levels of representation and allows the learner to explore and evaluate their hypothesis against statistical data over time. Examples of how this feature is utilised in this study will be reported in a later section.

Design of the study

Tasks

Three sets of predict-observe-explain (POE) tasks (White and Gunstone, 1992) were designed to elicit and confront students' alternative conceptions. The computer-based simulation activities were used in place of experimental activities normally used in POE tasks. A set of worksheets was given to the students in conjunction with the simulation activities so as to elicit students' prior ideas and conceptions and then examine how students react to the results of the simulations in order to find out how they interpreted the discrepancies between their prediction and the outcome. All the students were working in groups of two to three which encouraged them to discuss their ideas and decisions with their group members. When the researcher failed to fully understand the thinking process expressed by the students, the researcher requested clarification from the students. The conversations were tape recorded and transcribed as qualitative data reflecting the students' conceptualisation and thought processes.

The first set of POE tasks involved three simulations created using the phenotypic reproduction world. The first simulation involved two brown parent rabbits that were both homozygous dominant such that all offspring were brown; the second simulation involved two brown parent rabbits that were both heterozygous such that one quarter of the offspring were white; while the third involved one homozygous dominant brown parent and one homozygous recessive white parent such that all offspring were brown. For each simulation, after loading the simulation and before it was executed, the students were asked to predict the phenotypic mix of offspring and to write down their prediction. They then ran the simulation and recorded their observations. Where there was discrepancy between their prediction and observation, they would be asked to explain how the discrepancy came about.

The second set of tasks involved the use of the genotypic reproduction world to explore the variety of offspring combinations for different genotypic parental combinations. The students were first asked to write down the allelic key for all possible genotypes for a brown rabbit and a white rabbit respectively. They were then encouraged to place different pairs of parents on the world grid and then predict and observe the resulting offspring combinations. Finally, students were asked to write down the allelic key for the two parent rabbits in each of the three simulations in the first set of POE tasks.

The third task focused on developing students' understanding of the probabilistic nature of inheritance and how that relates to the concept of genetic ratio which many students understood to be a deterministic figure. Students were asked to place two heterozygous parents on the world grid and then read off from the statistical graph (or chart) the number of white and brown offspring at given time intervals and to calculate and record the respective ratios (see Figure 5). Next, they were asked if the ratio was a constant and to provide an explanation for why it was as they observed. Finally, the students were encouraged to examine the interaction rules for the reproduction world and use that to explain their observations.

Pre-test on misconceptions

Before the students undertook the POE tasks, a pencil-and-paper test was administered as a pre-test to find out the prior conceptions held by the students. The test consisted of seven open-ended questions that were drawn from Clough and Wood-Robinson (1985) and Lawson (1988). The test tackled four major concepts in genetics: firstly, the ideas of heterozygotes, homozygotes, dominant trait, and recessive trait; secondly, the idea that acquired characteristics were not inherited; thirdly, the probabilistic nature of the genetic ratio; and lastly, the definition of some technical terminology in genetics.

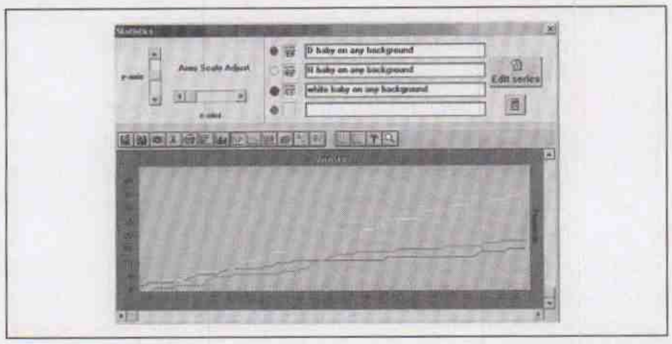

***Figure 5** The statistical tool in WM that allows the user to record and display the population statistics for defined entities over time.*

Subjects

The study was conducted in a Hong Kong high school with students mainly from lower middle class with average and above academic performance. Altogether 16 high school students from Grades 11 and 13 (seven from the science stream and five from the humanities stream) with varying backgrounds in genetics knowledge were invited to take part in this study, working in six groups of two to three students. As the Grade 11 students (aged 16 to 17 years) from the humanities stream had not received any instruction in genetics before, some instructional materials were provided to introduce them to the key concepts in Mendelian genetics after they had completed the first set of POE tasks. These included a short animation on Mendelian genetics from Encarta® and some printed materials from the same source.

Results and Discussion

Confusion and misconceptions resulting from instructions received

When the students' answers to the pre-test questions as well as the ideas elicited during the POE tasks were examined, it was found that the science stream students had a tendency to interpret situations and observations on the basis of not only their own intuitive ideas, but also the concepts learnt through the science curriculum, resulting in a more diverse collection of misconceptions.

In response to the pre-test item about acquired characteristics and inheritance, four out of five of the humanities stream students believed that if a white couple moved to live in Central Africa, the skin colour of their children would remain white. Reasons given included:

'The skin colour of the offspring at birth should be white, though it may become tanned due to increased exposure to the sunlight.'

'The skin colour of the baby is white because both parents are white in colour.'

'The environment would not affect the genetic composition.'

On the other hand, four of the nine Grade 11 science stream students believed that environmental factors would affect inheritance if the change involved is a gradual one. There appeared to be a misconception that the skin colour of the offspring may be affected if the parents move to a very hot sunny location, while sudden changes like lameness due to traffic accidents will not be inherited:

'The skin colour may become darker. This is because skin colour is a continuous variation.'

'As generations pass on, the skin of the offspring will become black in colour. It is due to the environmental change.'

'As generations pass on, their skin would be darker in colour. It just like when you have moved to USA for a long time, you will have an American accent.'

It appears that students in the science stream tended to interpret the various new genetic concepts they have learnt, such as evolution and natural selection, in ways that led to misconceptions. The belief that gradual change would affect the characteristics of the offspring was also previously documented by Lawson (1988).

The tendency to confuse learnt concepts and ideas was also clearly evident when the students performed the POE tasks. For example, a group of the science stream students were surprised to observe two brown rabbits giving birth to some white rabbits, and one of them remarked:

"Maybe it is because there is not enough nutrition, so when both identical babies grow in different environments they will look different afterwards."

Later, when the students were engaged in the third POE task, one group of science stream students had the following dialogue when they tried to explain why the genetic ratio varied instead of remaining constant over time:

Mei: Would the colour ratio (i.e. ratio of white: brown rabbits) of the offspring depend on environmental factors? I do not really think so, unless there is a sudden change in the environment. I do not think the colour is affected by the environment. I think they are determined from birth.

Researcher: How can you explain why the colour ratio changed (when calculated over different time intervals)?

Mei: I think it is due to sudden changes – mutation. Mutation is different from environment. I think that it is due to mutation but not environmental factors. Also I think the ratio still remains the same throughout.

Iris: If the parents give birth to the offspring at the same location all the time and the offspring grow up in the same place, they should be all brown. How come there is any white? Here in the world grid, the whole place is the Earth, right? Will there be any chance that one part of the earth (referring to the World Grid) is hotter or cooler than the other?

Researcher: No, it should be the same all through (the grid).

Amy: That is to say the environment is the same everywhere.

Mei: The environment should not affect the colour of the offspring. At most, they would be born white and only later on changed to black.

The above excerpts reveal that students had idiosyncratic ideas on mutation, environmental and genetic adaptation and that such ideas surface when they try to create explanations for discrepant observations.

Experiment-like simulations: eliciting more theorising based on prior ideas

Posner et al (1982) advocated the use of discrepant events to promote conceptual change, as students would be compelled to review their existing concepts critically when their observations contradict with prior beliefs. In this study, it was observed that in tackling the POE tasks, the students often had to make their ideas explicit in the context of creating explanations for discrepant observations. However, the consequence of these explorations and subsequent efforts at conflict resolution did not generally lead to the establishment of the scientifically accepted theories, just as experiments *per se* in science classes do not necessarily result in one single explanatory theory. Instead, possibly as a consequence of the iconic nature of the simulation environment, the students tended to theorise and build alternative explanations for the discrepant observations using their prior ideas (and misconceptions). One example of such theorising attempts is described below.

Over half of all the participating students predicted that brown rabbits would always give birth to brown rabbits only. The rationale for such prediction tended to be rather intuitive, drawing on analogies from other domains:

'... Because both parents are brown in colour, their offspring would also be brown.'

'It's just like a positive number (brown rabbit) plus positive number and the result is also positive, and negative number plus negative numbers the result is negative.'

When they observed white offspring being born from the brown parents, the explanations they attempted were also intuitive:

'Two brown rabbit may not necessarily give birth to a brown offspring because there might be some chemical changes when they mated. As a result it may give birth to a rabbit with different appearance, or something inside the rabbits were different.'

'Although the appearance of the two brown rabbits is the same, something inside may be different.'

Conflict resolution and socio-co-construction using iconic simulations

While theories created by students to explain for discrepant events might be intuitively grounded, the availability of an explorable simulation built on an iconic modelling environment was found to support deeper reflection and more rigorous discussion and co-construction when used in group settings. The varieties of explanations arising from the group discussion stimulated further explorations and debates:

Wing: Oh! Why there is a white rabbit?

Ling: Is it due to the fact that the parent rabbit gave birth to brown rabbits first then pass on to the white one?

Wah: Do you mean that the parent rabbits are running out of pigments so the colour will become paler and paler?

Ling: Yes, that is what I mean.

Wing: Really? Maybe it is due to the effect of radiation.

Wah: Hey! As I have mentioned before, the more tasty the food, the better the life will be. Therefore, there is a change inside the body of the rabbit and then it can produce a white rabbit.

Ling: Let us run the program again and see whether it produces the brown rabbit first or the white rabbit first.

Here, it is important to note that unlike a quantitative simulation, WM as an iconic modelling tool would allow the user to explore the simulation as if one is actually witnessing the reproduction of rabbits in a real situation with time and location information (which may be considered to be redundant from the point of view of teaching about Mendel's Law):

Wah: OK

Ling: Hey! You see they gave birth to the brown rabbit first then the white, but they gave birth to the brown rabbit again!

Wing: As I said it must be due to the effect of radiation.

Ling: Oh! My hypothesis is not correct.

Wah: But if it is due to the effect of radiation then the grass would also be affected. However, it is not.

Wing: Then there must be something inside the body of these two (parent) rabbits that are different from those in simulation 1.

As observed from the above dialogue, each of the three students actually came up with a different hypothesis to explain the birth of white offspring from two brown parent rabbits: the parent rabbit running out of pigments, the effect of radiation or the effect of good nutrition. Furthermore, the collaborative effort at co-

constructing a viable explanation using WM as a supportive exploratory platform helped them to reject these hypotheses and to look for an alternative explanation that builds on some innate quality of the parent rabbits.

Co-construction supported by multi-perspective visualisation

One very important and useful feature of WM as an iconic modelling tool was the dissociation of the iconic image of an entity from its functionality (i.e. its rules of interaction) such that one can provide multiple iconic visualisations for the same simulation. Taking advantage of this feature, students were given the opportunity to move between a phenotypic and a genotypic simulation, which proved to be very helpful in supporting collaborative co-construction. For example, when students were confronted with the observation that one brown parent and one white parent gave birth to brown rabbits only (most students predicted the offspring in this situation to be a mix of brown and white rabbits), one of the groups had the following dialogue when they were exploring the genotypic reproduction world:

Kin: Oh! So here are two brown rabbits, two pure breed brown rabbits.

Tak: True. What I have interpreted is that if you have two of these (homozygous dominant), the offspring will always be brown. (Drawing the Punnett square to illustrate his thinking.)

Kin: So this is the case for two pure breed brown rabbits. What if there is a brown rabbit with Tt, and with another pure breed white rabbit. What will be the colour of their offspring?

Tak: So there are four possibilities: Tt, Tt, tt and tt, half of the offspring will be white and half will be brown.

Kin: Oh! But why isn't it similar to the present situation?

Tak: I think that's because TT (in this case) is the pure brown whereas Tt is the hybrid. Therefore all offspring in this case are brown.

Kin: What about parent 2 (The one with Tt)? Is it the same as your prediction? I want to try that out on the program.

Iconic modelling and understanding genetic ratio as a probability

As mentioned earlier, research has consistently found the probabilistic understanding of genetic ratio to be difficult for learners (Longden, 1982; Kinnear, 1983). The statistical function in WM allows the user to get information about the total population of defined entities on the world grid as the simulation evolves, thus providing the user with an additional possibility of visualising global changes over time. This feature was exploited in the third POE task to help students understand the probabilistic nature of the genetic ratio, as can be illustrated through the students' dialogue below:

Lo: Oh! Why are the ratios different at time periods 10, 20 and so on?

Wong: Yeah, it is not equal to 3:1. That is strange.

Tang: Let us calculate the exact ratio and correct to 1 decimal place. 11:4 is equal to 2.75, 20:6 is equal to 3.33, 31:10 is equal to 3.1, and 46:15 is 3.06. It is not exactly equal to 3:1 and it seems that it is become larger and then smaller.

Wong: Um. Why? Maybe… Ah! I remember it is random. 3:1 is only an ideal ratio.

Lo: Yes, it is just like tossing a coin, 50% of having a tail is just an ideal case.

Tang: Let's run the program once more and see what happens.

Interactions with the simulations and subsequent exploration of time variations in population helped the students to understand better the concept of a probabilistic parameter — the idea that a predictable trend can result from an accumulation of random events.

Again, starting with intuitively based hypotheses, explorations in WM may help students to reject some of these initial ideas and move towards more scientifically accepted conceptualisations. For example, one group of science stream students started with the hypotheses that the genetic ratio was in fact deterministically 1:3 and that the variation recorded in the chart was due to change of rabbit coat colour resulting from post-natal environmental changes. The following is an excerpt from the students' dialogue as they tried to make sense of their observations:

Iris: However, in the statistics chart (provided by WM), if they are born white, this number in the chart would be recorded down and so the ratio should not be affected even if the offspring change later into black. I think this is not the reason.

Amy: Oh! Wait a minute let us look at the chart. I now understand! It's just like when you (a girl) are born, the next child of your mum is not necessarily a boy. Thus even though there is equal opportunity of having boys and girls, it does not mean that after having a boy you will have a girl.

Mei: Yes, you are right.

Amy: That is why it is random.

Exploration of rules in the model: genetic theory as a formal system

While a simulation presents only one possible explanatory model for a phenomenon and may not be able to eliminate other possibilities, to be able to examine the theory as a model with all the underlying assumptions made explicit makes it possible for the learner to see that a system with behaviour duly defined by a set of simple rules can give rise to the myriads of behavioural observations. In this study, in addition to exploring different simulations created by putting different combinations of parent rabbits onto the World Grid, students had the opportunity to examine the exact content of the rules of interactions that defined the behaviour of each of the entities in the world. Thus the model underlying the simulations became more transparent to the learner, allowing a deeper understanding of genetic theory as a formal system to be developed. The following is an excerpt of students' dialogue when they were inspecting and making sense of the rules:

Kin: I have seen some hints from the keys on the screen, about the capital T and the small letter t. (He was pointing at the rule name for one of the rules: Tt x Tt → TT, see Figure 3.)

Kin: The capital T represents the brown colour and the small t represents the white colour.

Tak: Let me see. (He opened up the rule and examined the contents)

Kin: So the brown rabbit (parent 2) now has the genotype

Tt, whereas tt will be that of the white rabbit.

Tak: Then we can find the genotype in the previous case.

Kin: In the previous case (task 1), having parent 1, all offspring are brown that means the genotype of the parents will be TT ...... On the other hand, for parent 2, even though the phenotype is brown, there are possibilities that the offspring are white because the genotype of the parents is Tt. Let us check it in the rule list.

They then examined the remaining rules that governed the simulation. In a later episode, they tried to find out the relationship between each of the rules that governed the entire simulation (how the complete set of rules in the entire reproduction world were related to each other). They began with inspecting the set of rules governing the behaviour of a heterozygous parent and the associated probability of firing for each of the rules (refer to lower left corner of Figure 2 for details):

Kin: What does the percentage represent?

Researcher: For example, Tt mates with Tt (Tt x Tt), then there is 25% probability that the offspring will be TT. And if it is not TT, then the probability of having tt will be 33%.

Kin: 33%? But I thought it would be 25%.

Tak: Yes, how come it is 33%?

Researcher: These rules are fired in a sequence, one by one, depending on whether a previous rule is fired. Can you follow?

Kin: I see, you mean that after failing to fire the rule for TT being born, which has a 25% probability, the chance of getting tt is 25% of the remaining 75% of the probability, which is 25/75, which is 33%.

Tak: And the same reason with the rest of the rules.

While it is impressive that these students were able to work out the mathematical technicalities associated with the constraints of the programming logic of WM, it is an undesirable feature of this environment which may interfere with students' learning of the concepts related to genetic ratio (In a newer version of WM, WM2000, a further rule firing logic was added to allow truly random firing probability to be defined, eliminating the need for such counter-intuitive definitions of probability under such situations. WM2000 is available from: http://worldmaker.cite.hku.hk.).

Educational implications

Previous research (Cavallo, 1996) suggested that part of the difficulty in understanding genetics was that the concepts were learnt in a disjointed manner without holistic understanding. Understanding of the genetic theories requires the understanding of not only the abstract conceptual entities that are not immediately observable or derivable from observation, but also the interactions among the entities that the theories postulate and how these relate to the observable genetic phenomena. In this study, it was observed that working collaboratively on POE tasks using iconic simulations built in WM encouraged students to make explicit their intuitive assumptions and to create hypotheses to account for discrepant observations. Such theorising activities have not been reported in previous research using quantitative simulations in genetics education. Intuitive theorisation of the students provides the teacher with valuable insights into the prior ideas held by the students, and also leads to further explorations and possible further confrontations with discrepant observations, providing valuable opportunities for students to make sense of various concepts and ideas in a holistic manner.

The possibility for WM to provide multiple iconic representations for the same simulation allowed students to explore the same genetic simulation using phenotypic or genotypic representation. It was observed that the opportunity to move between two different visualisations of the same phenomena helped students to co-construct their understanding towards a more scientifically accepted one.

The availability of a statistics function in WM allows the user to visualise both the instantaneous reproduction behaviour of selected parent animals as well as the global time variation of the different offspring populations. This was found to be extremely valuable in helping students to understand a very difficult concept: how probabilistic parameters like the genetic ratio could have a deterministic value and yet be derived from totally random probabilistic events.

It was further observed that though collaborative co-construction activities in WM may not necessarily lead to the elimination of intuitive, alternative ideas, the possibility for students to examine and explore the consequences of all the rules governing the genetic behaviour of the simulations built in WM did allow students to gain a deeper understanding of the issues and concepts involved in genetic theory as a formal, theoretical system that carries pervasive implications for all phenomena related to inheritance. In fact, there are greater learning opportunities provided by WM that still need to be unlocked: learning through the creation of new models by students' modification and creation of new rules and new entities (which may be either concrete or conceptual).

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Appendix

Suppliers

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