# Design criteria for learning and teaching genetics

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While learning and teaching difficulties in genetics have been abundantly explored and described, there has been less focus on the development and field-testing of strategies to address them. To inform the design of such a strategy a review study, focus group interviews with teachers, a case study of a traditional series of genetics lessons, student interviews, and content analysis of school genetics teaching were carried out. Specific difficulties reported in the literature were comparable to those perceived by Dutch teachers and found in the case study and the student interviews. The problems associated with the abstract and complex nature of genetics were studied in more detail. The separation of inheritance, reproduction and meiosis in the curriculum accounts for the abstract nature of genetics, while the different levels of biological organisation contribute to its complex nature. Finally, four design criteria are defined for a learning and teaching strategy to address these problems: linking the levels of organism, cell and molecule; explicitly connecting meiosis and inheritance; distinguishing the somatic and germ cell line in the context of the life cycle; and an active exploration of the relations between the levels of organisation by the students.
*Key words*: Biology education; Genetics; Learning and teaching difficulties; Design criteria

## Introduction

Genetics is a fundamental part of biology but is also relevant to everyday life. The applications and implications of genomics require better ‘genetic literacy’ through biology education. However, genetics is also one of the most difficult topics for both students and their teachers (Finley *et al*, 1982; Bahar *et al*,1999).

This article reports on the first part of a developmental research project (Knippels, 2002) and seeks to address the research question: *What are the main problems in secondary genetics education for Dutch teachers and students and how could these be addressed?* The project is meant to inform the design of a learning and teaching strategy, which will subsequently be developed, field-tested and revised.

After a review of the relevant literature, additional information was acquired through: focus-group interviews with Dutch teachers; a case study of a traditional series of genetics lessons; student interviews; and content analysis of school genetics. These activities were designed to identify the main problems and to inform the design of a learning and teaching strategy to address them.

## Review study

Much science education literature of the past two decades has dealt with learning and teaching genetics (e.g. Stewart, 1982; Smith, 1988; Kindfield, 1991, 1994; Stewart and Hafner, 1994). The review study on genetics education identified five major difficulties: a) the domain-specific vocabulary and terminology, b) the mathematical content of Mendelian genetics tasks, c) the cytological processes, d) the abstract nature of the subject in the biology curriculum and e) the complex nature of genetics: a macro-micro problem (Knippels, 2002).

These different problems are not isolated and may exacerbate each other: students face problems in representing genetics texts into schemes and symbols, and vice versa in reading schemes and symbols. Knowledge of the extensive genetic terminology is required to understand a classical genetics problem. However, students are often not familiar with the definitions of the genetics-related terms, and they may get confused because terms look and sound very similar, e.g. homologue, homologous, homozygous and homozygote (Bahar *et al*, 1999). Besides, students face problems due to misuse of genetic terms, the existence of synonyms and the occurrence of redundant and obsolete terminology (Kinnear, 1983; Cho *et al*, 1985; Pearson and Hughes, 1988a, 1988b). Moreover, they have to do mathematical calculations with symbols in solving the genetic cross problems, and to connect probabilistic reasoning with biological phenomena. Students often manipulate symbols and apply algorithms without correct insight into the underlying inheritance patterns (Thomson and Stewart, 1985). The Punnett Square is often used routinely by students without considering the probabilistic nature of meiosis and genetics (Kinnear, 1983).

The structuring of the biology curriculum in which the topic of meiosis is isolated from heredity adds to the abstract character of genetics. Students’ understanding of cell division processes appears to be limited, confused, and inconsistent. They make little distinction between mitosis and meiosis, and have poor understanding of the purpose, processes and products of cell division. Besides, students have difficulties with the chromosome concept. The homologue chromosomes concept is confusing to them, and they do not realise that sister chromatids carry the same alleles and consequently are identical (Brown, 1990; Lewis and Wood-Robinson, 2000; Lewis *et al*, 2000a, 2000b).

Students have poor understanding of genetic relationships, due to misunderstandings about the process of meiosis and the underlying chromosome behaviour. They encounter difficulties in linking the different genetics concepts of the macro-, micro and sub-micro level. Several science education researchers noted that when concepts and processes belong simultaneously to different levels of organisation, students have difficulties in grasping the subject (Bahar *et al*, 1999; Halldén, 1990).

## Focus group interviews

Most of the reviewed studies in genetics education were carried out in the United States and UK. Did the findings apply to secondary genetics education in the Netherlands? To find out the answer to this question and to explore the Dutch context, carefully designed focus group interviews with biology teachers were arranged (Knippels *et al*, 2000). Ten meaningful problem categories were extracted (Table 1) and only slight variations from the Anglo-Saxon countries were found.

After the focus group interviews, it was decided to concentrate on two salient problems in genetics education: the abstract and complex nature of genetics. The emphasis gradually shifted from deepening an understanding of the problems to finding potential solutions. To support this process, systems thinking was adopted as an overarching perspective (Von Bertalanffy, 1968). Systems thinking enables different levels of biological organisation (e.g. molecule, cell and organism) to be first distinguished, then related. Biological concepts can thus be matched with specific levels of biological organisation.

## Case study

In the case study, 13 lessons of a traditional general upper-secondary genetics course were observed and audio-taped. The open interview method was used to clarify the rationale of the genetics teaching practice of the teacher involved (who had many years' experience). The 22 students of the class were asked to keep a personal notebook in which to reflect on their learning outcomes, perceived difficulties, and questions.

The students had already completed a basic genetics course in the second year of lower secondary education. The observed lessons focused on solving genetics tasks, in particular mono- and dihybrid crosses (this is common practice in traditional upper-secondary genetics education). Students were asked to solve multiple genetics problems and to calculate the probabilities of specific traits in the next generation.

The personal logbooks of the students and their questions during the lessons showed that they initially struggled with the multiple genetics terms and had difficulty in solving the genetics problems. It seemed that they learned by simply rehearsing a lot of genetics problems, often through trial-and-error, and that they did not really grasp the concepts. Bianca's logbook shows no real understanding:

> Genetics is difficult for me. I always start solving a genetics problem by writing down the information given in a task. Then I ask myself 'And what do I do now?' I often ask my classmates or my teacher for help, and together we manage, because everyone can take part in solving the problem. Looking at the answer I always think 'Of course, actually it's logical!' My only problem is that I often don't know how to continue. Apart from that, I understand everything.

Table 1. The main problems in learning and teaching genetics perceived by Dutch upper-secondary school biology teachers (n=19) in random order.

| Category | Description |
|---|---|
| 1. Abstract nature | Alienation from real biological phenomena due to lack of connection between inheritance and sexual reproduction in general, and meiosis in particular. |
| 2. Complexity | Inheritance has to do with all levels of biological organisation and an adequate understanding of genetics requires 'to-and-fro' thinking between molecular, cellular, organism, and population level. Simplification of inheritance easily leads to conceptual problems. |
| 3. Probabilistic reasoning | Students who perform poorly in mathematics often also do so when solving genetic problems; see also differences between students (10). |
| 4. Image | Inheritance may be perceived as a difficult topic in biology, resulting in poor motivation or a tendency to give up. |
| 5. Examinations | Mendelian genetics is just a small part of the final exam, consequently not much time is allotted to this difficult subject, although spending some extra time would be advantageous. Current practice is to teach and learn 'tricks' instead of insightful problem-solving behaviour. |
| 6. Terminology | Genetics is rich in terminology, but not all terms are necessary for adequate understanding. Furthermore, students are unwilling to memorise relevant terms; see also image (4). In addition, teachers and authors of curriculum materials do not always use terms consistently and explicitly. Inadequate translations of terms from English into Dutch (e.g. 'sex-linked') and politically correct language (e.g. 'genetic modification' instead of 'genetic manipulation') can also result in misunderstanding. |
| 7. Pedigrees, Punnett Square diagrams and symbolising | Students face problems in representing and reading genetic knowledge in(to) schemes and symbolising and symbols; see also problem-solving (8). These problems may increase in connection with the abstract nature of genetics (1) and its richness in terminology (6). |
| 8. Problem-solving | Students not only have difficulties with the representation of problems (7), but they also lack problem-solving and reading skills. |
| 9. Cell division | Students have an inadequate understanding of the process of meiosis, and do not always understand the differences between mitosis and meiosis. Consequently, students acquire a poor conceptual basis of genetics. |
| 10. Differences between students | Relevant prior knowledge and cognitive maturity is required for an adequate understanding of genetics. Students may differ in these respects; see also image (4). Furthermore, differences may also be related to opting for (or out of) chemistry and mathematics courses. |

Bianca has difficulties arriving at an answer insightfully and independently. For that, she needs to connect information and symbols in the genetics task with biological phenomena. A quotation from Susan's personal logbook exemplifies that she did not understand what exactly is depicted in a Punnett Square:

> I have discovered that genetics is really difficult to understand. […]
> It is not clear to me how you exactly build up a Punnett Square. I don't know how many possibilities you can depict horizontally and how many vertically in crossbreeding.

Apparently, she did not appreciate that the Punnett Square depicts the possible gametes from the parents bearing the given trait. When students do not see the relationship with the *preceding process of meiosis*, resulting in the formation of gametes, the Punnett Square becomes a biologically meaningless diagram and tool. And yet the teacher had mentioned the preceding cell division process in his explanation of a genetics cross problem. Evidently, this was not sufficient.

From observing the genetics lessons and examining the difficulties expressed in the students' personal logbooks, the problems with the abstract and complex nature of genetics in classroom practice were evident. Most students lack a meaningful insight into genetics, for example they use algorithms to solve genetics tasks or try to do so by trial-and-error. As a consequence they have difficulties in explaining their answers, or how some hereditary phenomena occur.

Consequently, genetics education should not primarily focus on solving genetics tasks, but should start with concrete features and should emphasise the basics. The abstract and complex nature is compounded when students do not grasp the relationships between the concepts at different levels of biological organisation – in particular the relationship between sexual reproduction and inheritance, in which the crucial process of meiosis is embedded. Instead of carrying out a lot of genetic cross exercises, we prefer to emphasise the main lines of biological reasoning. In order to help students understand and discover these relationships by themselves, an 'active' learning approach is needed because just being told about these relationships was clearly not sufficient.

The relationship between (sexual) reproduction, including meiosis, and inheritance, is one main theme: specifically, the germ cell line in a life cycle. The second theme is that of the somatic cell line: this includes the concept that all cells of an organism have the same chromosomes or genetic information, due to continuing mitosis starting at the zygote.

## Student interviews

In order to find out to what extent students are able to distinguish these two main themes, six out of the 22 students involved in the case study (four girls and two boys, aged 16-17) were interviewed. The individual interviews were introduced to them as a discussion about the way genetic information is passed on to succeeding generations, and how genetic information is passed on within our bodies. Actually, they were asked to think about the effect on the offspring when a mutation occurs in a somatic cell and in a gamete. They were also asked to explain why cells in a body differ in form and function, although they contain the same chromosomes. Finally, students were asked what they thought to be the connection between what had been discussed in the interview, and the genetic crosses dealt with in the lessons. The interviewer asked for clarification or substantiation, or encouraged a student when he or she got stuck.

Afterwards, another six students not involved in the case study (all girls, aged 15-16) were interviewed. These students had only been given a basic introduction to genetics in a lower-secondary biology class. These latter interviews focused on students' notions of genetic traits, their perceptions of inheritance and their explanations of passing on genetic information.

The interviews were audio-taped, transcribed and, subsequently, analysed by close reading of the protocols, and highlighting the genetics-reasoning patterns of the students.

The interviews showed that most of the six students involved in the case study were well aware that all somatic cells in a person contain the same genetic information, that they are formed by a cell division process that copies the chromosomes, and that they are not involved in sexual reproduction. Most students were able to discover the connections themselves, albeit with some help.

However, all six students involved in the case study experienced difficulties in explaining the germ cell line. They realised that both parents pass on genetic information to their offspring, but they were confused about what exactly is passed on, and what the relationship is between the process and products of meiosis. An extract from the interview with Paula illustrates this confusion (R is the researcher):

R: Could there also be cells without chromosomes?
Paula: No I don't think so, I don't know.
R: How do those cells originate in your body?
Paula: By division. Mitosis, meiosis, one of those two I think.
R: Yes, those are indeed two important processes, mitosis and meiosis. Can you indicate the most important difference between the two?
Paula: Yeah, no! That is what I'm wondering each time, what actually the difference is. I know we learnt both last year, and then I knew it. But I have really forgotten it. I was thinking about this yesterday in class, I didn't know the difference. I actually don't know… yes the meiosis is the reduction division or something like that, I don't know.
[…]
Paula: And this is with reproduction cells and the other with normal cells. I don't know it exactly I just guess.
R: Well it doesn't matter. We will try to solve the problem together. If meiosis is for reproduction cells and mitosis for other cells, as you say, what is the difference between those two? Why should there be two cell division processes, what could be the function?
Paula: Yeah that is why, I don't know, I'm guessing reproduction cells and other cells.
R: Well that is correct. The one has to do with reproduction cells and the other with the other cells in your body. When we can find out what the difference is between reproduction cells and body cells, than we can also reason why there are two different cell division processes.
[…]
Paula: Well, father gives 23 chromosomes, so that makes me doubting. He does not give uhm, he has 46, but he doesn't give all the 46. It is only a part.
R: You say he gives 23 chromosomes?
Paula: Doesn't he? It is 46 isn't it, 23 of both.

So, by comparing the somatic cell line and the germ cell line in the life cycle, these students were encouraged to articulate their lack of understanding of the mechanism of inheritance. This enables a new start to be made in teaching and learning genetics.

The students not involved in the case study readily mentioned genetic traits like hair and eye colour, height and intelligence. They also realised that traits are determined by the environment as well, for example through the upbringing and through imitating behaviour.

These students associated inheritance with passing on 'something' to the next generation; some backed up this answer with 'chromosomes' and/or 'genes'. It was striking that most students used their family as an example in their explanations; none referred to plants or animals. They made unprompted comparisons between themselves, their brothers and sisters, their parents and grandparents, to decide whether or not something could be hereditary. When students got stuck in their reasoning, it was often helpful to mention their parents or grandparents, e.g. "What do you think your parents pass on via the egg or sperm cell?" The interviewer also prompted to them to switch backwards-and-forwards between the organism and the cellular level.

The two rounds of interviews revealed the same kind of difficulties in relating genetic traits on the level of the organism with chromosomes and gamete formation by meiosis at the cellular level. In addition, the interviews suggested that genetics lessons should start with examples students are familiar with, i.e. on the level of the organism, in order to motivate them and help them to ask meaningful questions.

## Content analysis

Schoolbooks strongly influence teaching practice, in particular the selection and sequencing of subject matter. A quick scan of the chapter on inheritance in the most frequently used textbook revealed that the arrangement of the content did not meet our criteria for adequate sequencing, i.e. starting on the level of the visible organism and gradually descending to the cellular level not visible with the naked eye. Moreover, the relationship between sexual reproduction, meiosis and inheritance remains unstated. To see if these findings apply to other biology schoolbooks as well, three recently revised Dutch upper-secondary biology textbooks were analysed. The content analysis focused on how textbooks deal with the levels of biological organisation, and how they relate meiosis and inheritance. In addition, the issue of whether or not the genetics terms were attached to the right levels of biological organisation (organism, cell or molecule) was checked. From each textbook two chapters were analysed, one on meiosis and one on Mendelian inheritance.

The main findings of the content analysis of the three textbooks were:

- the textbooks failed to start on a phenomenal level and gradually descend to the lower levels
- the textbooks inconsistently applied the levels of biological organisation and the corresponding genetics terms (vocabulary); this may complicate learning genetics
- relationships between different genetics concepts attached to the various levels of biological organisation were not made explicit. Unstated changes of level of biological organisation were found in the analysed texts. Terms such as 'dominant' and 'recessive' should be related to allele, and 'homozygote' and 'heterozygote' should be related to genotype, e.g. 'an individual with a heterozygote genotype'.

So, the content analysis of three favourite Dutch biology textbooks showed that no explicit attention was paid to levels of biological organisation in the chapters on meiosis and inheritance. Moreover, the conceptual relationships between these chapters were not made explicit. The conclusion was therefore made that textbooks can be an important obstacle in learning genetics.

## Conclusions and educational implications

Adopting a systems perspective and relating the outcomes of the different explorative research activities deepened our understanding of the key difficulties in learning and teaching genetics in the Dutch context. This approach also provided indications on how to address them.

In teaching practice, a separation in time and space of the topics inheritance, reproduction and meiosis seems to be responsible for the abstract nature of the subject. Not using contexts from everyday life or problems that have personal or societal relevance adds to the abstract nature of genetics and to a loss of motivation amongst students.

Genetics is made more complex because of the different levels of biological organisation involved in heredity, and consequently the use of different vocabularies. Neglecting to interrelate the molecular, cellular, organism and population aspects causes learning difficulties, and the different structures and processes of these levels compound the problems. Students trying to learn genetics get into trouble, because biology teachers and schoolbook authors often implicitly jump from one level to another. Extensive genetic terminology adds to the difficulties that students experience.

The results from the review study and the focus group interviews indicate that it is important to adequately sequence the subject matter, i.e. according to the levels of biological organisation, and to pay attention to the relationship between inheritance, sexual reproduction and meiosis.

The case study suggests that the focus should not be on solving traditional genetic cross problems, but on interconnecting sexual reproduction, meiosis and genetic traits. These relationships were explored in the student interviews, by distinguishing the somatic cell line and the germ cell line, and relating these to mitosis and meiosis. This proved to be a promising approach. The student interviews also showed that lessons should start on the phenomenal organism level, preferably by focusing on similarities and differences in family traits, and that an adequate understanding requires consistent references between the levels of biological organisation

From the content analysis of schoolbooks it can be concluded that the sequencing of contents and activities in the learning and teaching strategy and materials should not follow the standard biology textbooks. Instead, the interrelationships between sexual reproduction, meiosis and inheritance and the levels of biological organisation should be made clear.

Finally, our findings result in the following four design criteria, which a learning and teaching strategy should meet in order to cope with the abstract and complex nature of genetics in biology education:

1. To adequately sequence the subject matter, genetics education should start on the phenomenal level of the organism that students are familiar with, i.e. their family, and should gradually descend to the cellular level. However, consistent references

between the different levels of biological organisation should be included.

2. The relationship between meiosis and inheritance should be dealt with explicitly.
3. Two main cell lines, the somatic line (mitosis) and the germ line (meiosis) should be distinguished in the setting of the life cycle.
4. Students should actively explore the relationships between the levels of biological organisation themselves, guided by the structure of the learning activities and/or by the teacher.

Such a learning and teaching strategy, the so-called *yo-yo learning and teaching strategy*, is being developed and field-tested in the second part of the developmental research project (Knippels, 2002).

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