Challenges in Understanding Meiosis: Fostering Metaconceptual Awareness among University Biology Students

Authors: Murtonen, M., Nokkala, C. & Södervik, I.

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Abstract

In this study, firstly, university biology students' conceptual understanding and potential misconceptions concerning meiosis were studied. Secondly, an easily applicable drawing task was used to foster students' metaconceptual awareness which would help them to reach conceptual change. A quasi-experimental design with a non-equivalent control group was conducted. The students (*N* = 82) were divided into experimental and control groups. The control groups attended traditional teaching, i.e. lectures with practicals, whilst the experimental groups had an additional activating task before practicals. In the activating task, the students drew the selected phases of meiosis and marked given concepts of meiosis in the drawing. The drawings were scored and the solutions were discussed in detail with the students. After the activating task, the traditional practicals were held for both groups. After a week, both experimental and control groups were given the same task. The results show that students in the experimental group understood meiosis significantly better than the control group, who had more misconceptions after the instruction compared to the experimental group. Thus, fostering students' metaconceptual awareness is crucial and relatively easy to apply, also in higher education.

Keywords: Meiosis, prior knowledge, metaconceptual awareness, conceptual change, higher education

Introduction

The common instructional challenge in European universities is the heterogeneity of students. Particularly in introductory courses, such as in biology, students' backgrounds are different and hence, the quality of their prior knowledge often varies a lot. Some students have a great amount of relevant prior knowledge, whereas others may have lots of unscientific prior conceptions about the content to be studied. This previous knowledge, that is a necessary prerequisite for all conceptual learning, may hinder learning if there are discrepancies between the old 'knowledge' and new information. This paradox of learning (Sinatra & Mason, 2013) poses a challenge for science instruction and therefore, there is a real need to develop effective and economical ways to support students' prerequisites to learn complex contents. The concept of meiosis has proved to be one of those concepts that is very challenging for some students to understand.

Previous research also at university level has conclusively shown that students come to science lessons loaded with expectations, previous knowledge and prior conceptions that sometimes significantly contradict the scientific view (see e.g. Duit & Tragust, 2003; Broughton, Sinatra & Nussbaum, 2013; Authors, 2016). Thus, to reach a scientific understanding often means reorganising one's knowledge structures, which often requires abandoning certain existing conceptions—a process that usually happens gradually and suggests intentional learning and teaching (e.g. Chi & Roscoe, 2002; Sinatra & Pintrich, 2003). This kind of learning is described using the theories of *conceptual change* (see e.g. Limón & Mason, 2002; Posner et al., 1982; Vosniadou, 1994). Achieving conceptual change is demanding and it suggests that the learner becomes dissatisfied with his/her previous conceptions, i.e. s/he becomes aware of the discrepancies between the scientific model and his/her previous ideas, which may result in a cognitive conflict. Cognitive conflict can be defined as mental discomfort that manifests when the coherence of one's knowledge structures is threatened. Cognitive conflict as such does not automatically result in a conceptual change, because even when students are confronted with contradictory information, they may not often experience a real need to change their prior ideas.

Therefore, it is crucial that so called *metaconceptual awareness* starts to guide the learning process to solve the cognitive conflict successfully (see Limón, 2001; Vosniadou & Ioannides, 1998). Metaconceptual awareness means that one becomes aware of the discrepancies between his/her previous conceptions and the scientific explanation, is able to weigh them critically and to most extent is willing to change his/her earlier conceptions. Metaconceptual awareness is usually a prerequisite for conceptual change because it induces dissatisfaction with one's previous inaccurate conceptions (see Broughton, Sinatra & Nussbaum, 2013; Lombardi, Sinatra & Nussbaum, 2013; Posner et al., 1982; Vosniadou, Ioannides, Dimitrakopoulou & Papademetriou, 2001).

As metaconceptual awareness usually is a crucial part of a successful learning situation, learning researchers have started to innovate materials and interventions targeted to awake students' metaconceptual awareness. Yilmaz, Tekkaya and Sungur (2011) reported a study that compared three different ways of teaching: the traditional, a prediction/discussion based learning cycle, and a conceptual change text teaching. The last two outperformed the traditional teaching, indicating that instruction that takes into consideration students' pre-existing knowledge and encourage students to be active participants, as well as to work collaboratively, result in better understanding than the traditional instruction. Furthermore, so called refuational texts that aim to support reader to notice differences between his/her original beliefs and scientific explanation (Hynd, 2001) have shown their potential to support awakening of readers metaconceptual awareness and further conceptual change in higher education (*Authors*, 2014). However, there is a need for effective tools that can be easily and lightly implemented and that would activate students to consider their level and quality of prior knowledge and later, their learning results.

It is well documented fact that understanding cell division processes, mitosis and meiosis, poses challenges for students in different educational levels from primary school to higher education (see e.g. Brown, 1990; Dikmenli, 2010; Newman, Catavero & Wright, 2012; Quinn, Pegg & Panizzon, 2009). It is also known that in general, genetics is often experienced as a difficult subject to learn also by university biology students (Kiliç & Sağlam, 2013; Kindfield, 1991; Quinn et al., 2009), but the conceptions about meiosis among university biology students is a less explored area and learning researchers have only a limited understanding about how to support the learning of complex scientific contents, such as meiosis, at university level.

The contents of mitosis and meiosis are studied several times during the school years already before university. However, these concepts are often presented in textbooks as lists that may be studied using rote memory without deeper understanding. Quinn, Pegg & Panizzon (2009) studied first year university students' understanding of meiosis and concluded that there are several areas of confusion apparent in student's understanding of meiosis. According to them, meiosis is difficult to understand because of its complexity: it lies at the intersection of the major biological substudies of cell theory, evolution, genetics and reproduction. In addition, students need to master many subordinate concepts, such as DNA, genes and chromosomes, and how these are related in terms of structure and function (see also Smith, 1991). On the basis of their study, Newman et al. (2012) suggested that although students understand the chromosome structure, they fail to transfer their knowledge into explaining macromolecular phenomena. Therefore, the problem lies at the level of understanding: students understand the information 'bits' of meiosis but do not understand the critical connections related to it.

In addition, the challenges of learning relate to centraldifferences between meiosis and the mitotic cell division pattern, which is the number of chromosome separation steps that follow chromosome duplication; mitotic cells separate chromosomes in a single step, whereas meiosis is characterized by two sequential separation steps — meiosis I and meiosis II. Meiosis II is an equational division very similar to mitosis. Thus, if students study these contents only superficially, there is a great chance that these phases of the processes become poorly learnt.

Research rationale and purposes

University teachers may assume that their students already understand the process of meiosis when entering university, and thus meiosis may be taught only briefly as a recap. Also, curriculum design in universities may not take into account students who do not fully understand meiosis, so there may be only a very short time allocated for teaching this concept. Thus, some students' may possess their possible misconceptions even when graduating university. University teachers thus need easily applicable methods to foster their students' learning of meiosis.

The first purpose of this study was to investigate what kind of conceptual challenges university students' have in understanding of the content of meiosis in an introductory course of genetics. The second task was to investigate if learning could be fostered via an easily applicable task that aims to activate students' metaconceptual awareness in a relatively short period of time.

Methods

To explore students' conceptions of meiosis and to test the power of a novel teaching method that aimed to foster metaconceptual awareness in order to generate conceptual change, we used a quasi-experimental design. In this design, the novel teaching method meant an additional drawing task with a discussion session for the experimental group in the beginning of a laboratory working session, while the traditional teaching method for the control group did not include a drawing task in that phase (see Figure 1). This meant that unlike in typical quasi-experimental designs, we did not conduct the test for the control group as pre-test, because the test, i.e. the drawing task itself acted as a treatment for the experimental group. Thus, we call the observation situations as Measurement 1 and Measurement 2 (see Figure 1), and the control group participated only in the Measurement 2. The experiment offered at the same time data about students' understanding of the concept of meiosis.

The design of the study was quasi-experimental due to the facts that all students were from the same university, the sample lacks the true randomization of the groups, and the setting included a non-equivalent control group (Cohen, Manion & Morrison, 2001). Randomness was pursued by dividing the biology major students into experimental and control groups in alphabetical order. There were also minor students on the course who were allowed to select a group that was suitable for their timetables, since they had more troubles with fitting this course to their program. Once the groups had been formed, the experimental and control groups were selected by drawing lots.

The data was collected on a course entitled 'Physiology and Genetics of Organisms' which included one 1-hour lecture and one 4-hour session of laboratory work dedicated to the study of meiosis. In addition, meiosis appeared briefly as a topic in a later laboratory session. Thus, this university presents an example of a university that uses only a very brief time to teach meiosis.

Due to the small year group sizes of biology students at the university, we conducted the test over two consecutive years. A total of 82 students participated in the study (N = 39 in the first year and N = 43 in the second year). The course was administered in a similar phase of the semester in both years and the lectures and laboratory works were conducted by the same teacher. Background information on the students in the two different groups and the year in which they participated in the study, such as their previous study success in university, was compared and no differences were found. Thus, the two groups are treated as one group in this study.

The Task. The task aiming to foster students metaconceptual awareness commenced by assigning the experimental group a drawing task on the concept to be learnt, i.e. meiosis, at the beginning of a laboratory working session. Based on the fact that metaphases of mitosis and meiosis have some fundamental differences, the task focused on comparing metaphases between mitosis and meiosis. Hence, the students were instructed to draw schematic pictures of the mitotic metaphase, metaphase I and metaphase II, and mark five given concepts (bivalent, diploid/haploid chromosome number, reductional/equational division) in the correct places on the drawings. In the correct pictorial presentation, one concept should be marked in two places, i.e. the total amount of properly written concepts was six. The diploid chromosome number was given as $2n = 6$ and all chromosomes were told to be metacentric.

After students had drawn their pictures, which corresponds to pre-test and is called the Measurement 1 in this quasi-experimental design (See Figure 1), the task papers were collected and immediately copied. The teacher kept the original drawings and gave students a copy of their own drawing. The experimental treatment then followed, i.e. the drawing task was then discussed together with the students and the correct answers were presented. The students were able to compare their own drawing against the correct model presented and make possible changes to their drawings as a note. The most common misunderstandings of meiosis were also discussed with students. The aim of this task, including the discussion, was to create a cognitive conflict between students' previous knowledge and the new information and thus result in a conceptual change towards the more scientific conception. This procedure was considered as the experimental treatment in our design. After the activating task, the students continued the traditional laboratory sessions where the teacher demonstrated the complete process of meiosis and the students subsequently searched and identified various phases of meiosis from microscope slides and drew sketches of them in their workbook. At the end of the session the teacher inspected the drawings and accepted them or returned the student to the microscope.

The control group participated in a similar traditional laboratory session, as did the experimental group, but they had a measurement only after the laboratory session (see Figure 1). Thus, they also did the activating task during the course. This procedure ensured high quality learning also for the control group students.

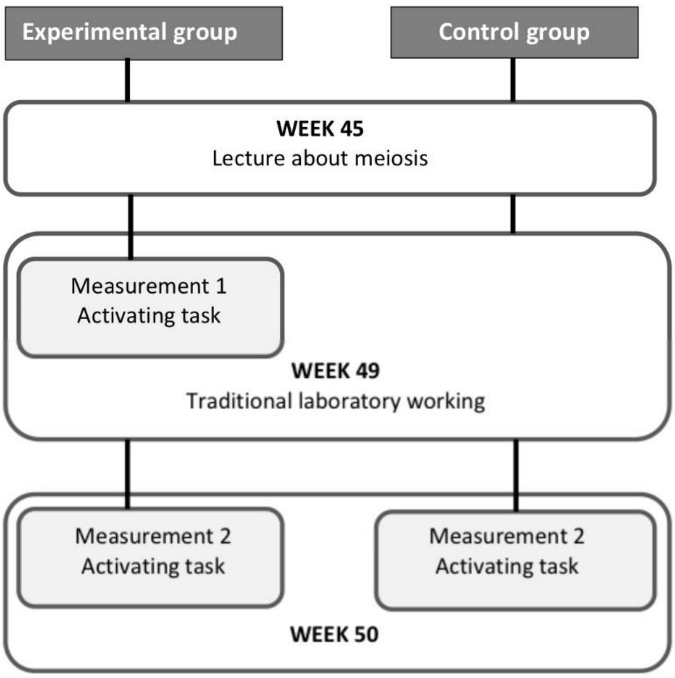


Figure 1. The quasi-experimental design of the study.

Analysis and rating of the drawings.

Each drawing scored between 0-3 points and each correct concept marking scored 1 point. If the concept was indicated incorrectly 1 point was deducted. Therefore the highest possible score was 15 points and the drawings totaled 9 points or 60 % of the score. The drawings were given more weight since it is possible to memorize which concepts are connected to which phase without a profound understanding of the concepts or meiotic process. In this paper, the students' drawings are referred to by an abbreviation, informing the reader about the student's group (E = experimental or C = control group) and study status (Maj = majority or Min = minority), and with numbers in numerical order to refer to a certain student.

Results

Student's understanding of the concept of meiosis. An example of the correct pictorial representation with the highest score (15 points) is shown in Figure 2 (student EMaj1), in which the drawings are clear and the concepts are marked unambiguously. This drawing was produced by a student in the experimental group in the Measurement 2. In general, the quality of drawings in the experimental group was high in the Measurement 2 and lack of full marks often resulted from missing concept markings rather than mistakes in drawings.

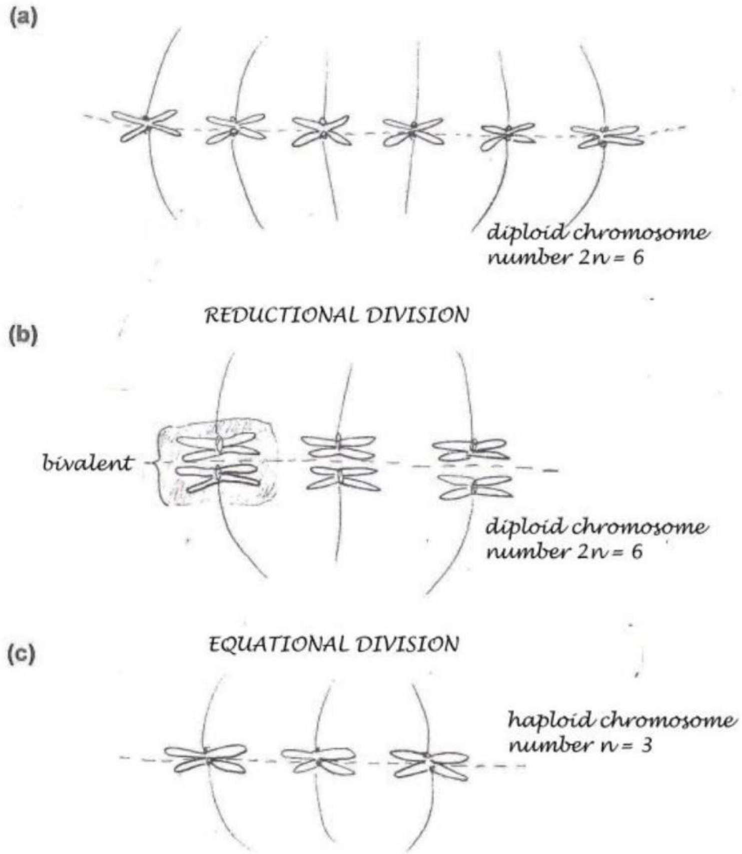


Figure 2. Example of a correct pictorial representation of meiosis (major student EMaj1, Measurement 2).

However, several students had misconceptions about meiosis (see Table 1). In order to gain an understanding of the students' misconceptions, a table was created to show the scoring and misconceptions. The most common misconceptions were associated with the concepts of bivalent and diploidy/haploidy and this has also been observed in earlier studies (Dikmenli 2010; Kinfield 1991; Newman et al. 2012; Wright & Newman 2011). These deficiencies and misinterpretations in students' answers indicate that fundamental differences between mitosis and meiosis were not correctly understood. Surprisingly, the concept of chromosome number also seemed to be poorly constructed by some students (Table 1). As the diploid chromosome number was given to be 2n=6, drawings showing any multiple of 3 elements indicated some understanding, but drawings with multiples of 4 or 5 elements were also produced. The number of elements was different in the three drawings produced by some students. This indicates a complete lack of understanding of meiosis as a process where phases occur in a continuum.

Table 1 Misconceptions found in students' drawings

Table 1. Table of misconceptions found in students' drawings.

Misconceptions		Experimental group, N = 41		Control group, N = 41
		Week 49	Week 50	Week 50
Haploid (incorrect or missing)		10	4	10
Diploid (incorrect or missing)		19	8	26
Chromosome number incorrect in drawing	a (mitosis)	14	3	12
	b (metaphase I)	11	10	13
	c (metaphase II)	11	1	6
Bivalent (incorrect or missing)		30	19	29
Reductional division (incorrect or missing)		11	4	7
Equational division (incorrect or missing)		11	4	6
Corresponding anaphase instead of metaphase	a	5		6
	b	4	2	4
	c	8	4	9

With the exception of the chromosome number in metaphase I, the number of misconceptions was reduced in the experimental group in every category when comparing results from Measurement 1 and 2, while the number and distribution of misconceptions were essentially the same in the control group after Measurement 2 as in the experimental group after Measurement 1. The wrong chromosome number in metaphase I, even in the Measurement 2 in the experimental group, was often coupled with incorrect conception of bivalent or haploidy/diploidy. A similar improvement in scores in a pretest-posttest study which measured students' understanding of ploidy level was also observed by Wright and Newman (2011). Their study involved testing students before and after an interactive lesson.

In Figures 3 and 4 below, some of the most common misconceptions in the students' original drawings are presented in more detail. One common mistake was representing metaphase I as essentially similar to the mitotic metaphase, i.e. individual chromosomes were arranged along the equatorial plane, the chromosome number being the same (Figure 3) or half of that in mitotic metaphase (Figure 4). An incorrectly pictured metaphase II is bound to follow such presentations of metaphase I (Figures 3 and 4).

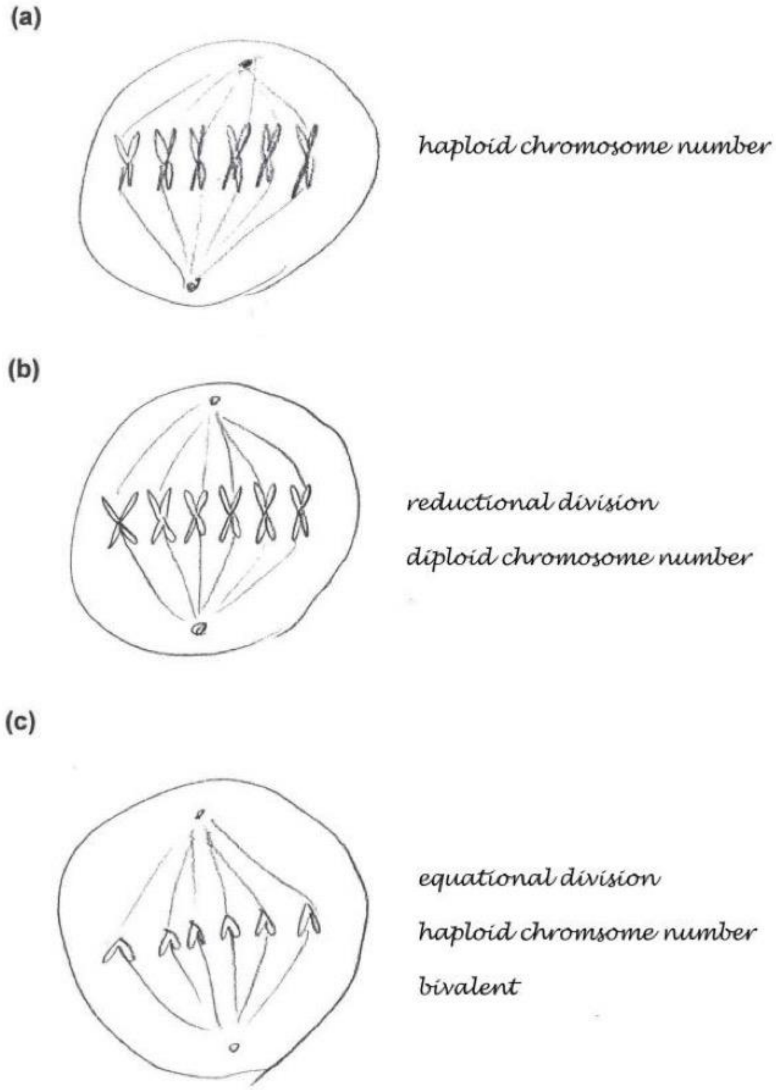
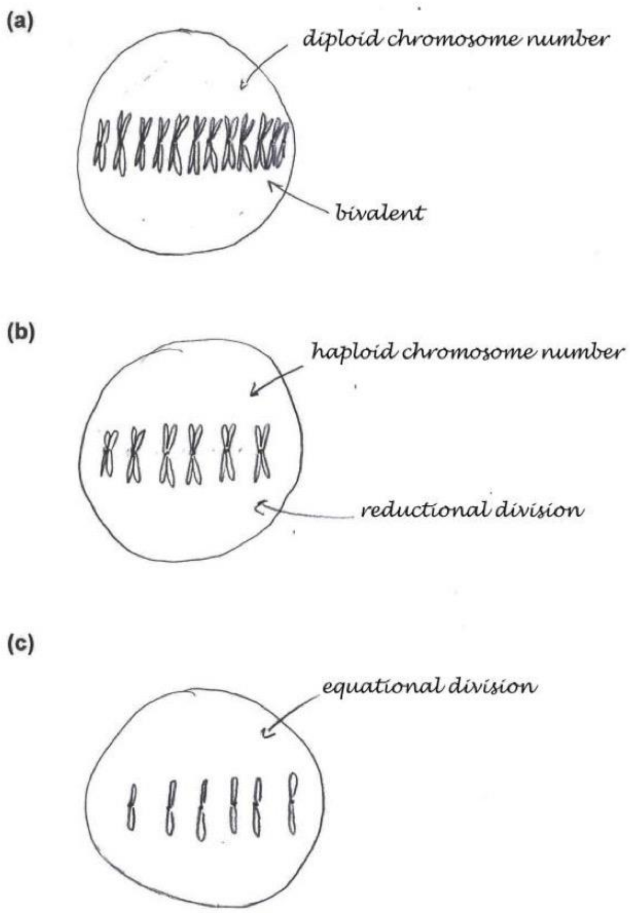


Figure 3. Vague understanding of meiosis. (Student CMaj1, only the Measurement 2)



Insert Figure 4 around here, please

Figure 4. Vague understanding of meiosis. An example of misconceptions at the end of the course (student CMin1, only the Measurement 2)

The concept of bivalent was missing in the majority of drawings in the Measurement 1 or was ambiguously marked on the drawing (Table 1). Notably, after the discussion which followed the Measurement 1 and traditional laboratory session, the concept of bivalent still remained poorly understood and caused a number of scores to be reduced after the Measurement 2. The concept appeared incorrectly or ambiguously marked both in mitotic metaphase (Figure 4, a), metaphase I (Figure 5, Measurement 1) and metaphase II (Figure 3, c). In a number of cases bivalent was synonymized with doubled chromosome (Figures 4 and 5, Measurement 1).

Different misconceptions of the diploid and haploid chromosome number were numerous (Table 1), including mixing the state of the chromosome, for example, the daughter chromosome (single chromatid) connected to haploidy and doubled chromosome (two sister chromatids) to diploidy. In addition, associating it simultaneously (Figure 6, Measurement 1 a, c) or independently (Figure 6, Measurement 1 b) with anaphase groups and on one occasion, completely similar drawings were labeled haploid or diploid whilst representing different phases (Figure 3 a, b).

A somewhat unexpected, but common mistake in drawings, was representing the corresponding/following anaphase instead of a particular metaphase. This occurred seventeen times in the Measurement 1 in the experimental group and nineteen times in the control group (Figure 5, Measurement 1), and remarkably six times in the measurement 2 (Figure 5, Measurement 2 c; Figure 6, Measurement 2 b). Some students did not produce any drawing or presented only mitotic metaphase (Figure 7, Measurement 1). In the example presented in Figure 7 (Measurement 1), the student has memorized, somewhat vaguely, the association of a concept with a certain phase in meiosis, but as the incorrect placement of equational and reductional divisions reveals, has no actual understanding of what is happening.

Effect of the activating task on experimental group students' understanding of meiosis. Students showed considerable progress in understanding meiosis when the measurement was repeated in the experimental group, as is indicated by a significantly higher average score in the Measurement 2 (Table 2). In some cases the progress was very dramatic (Figure 7).

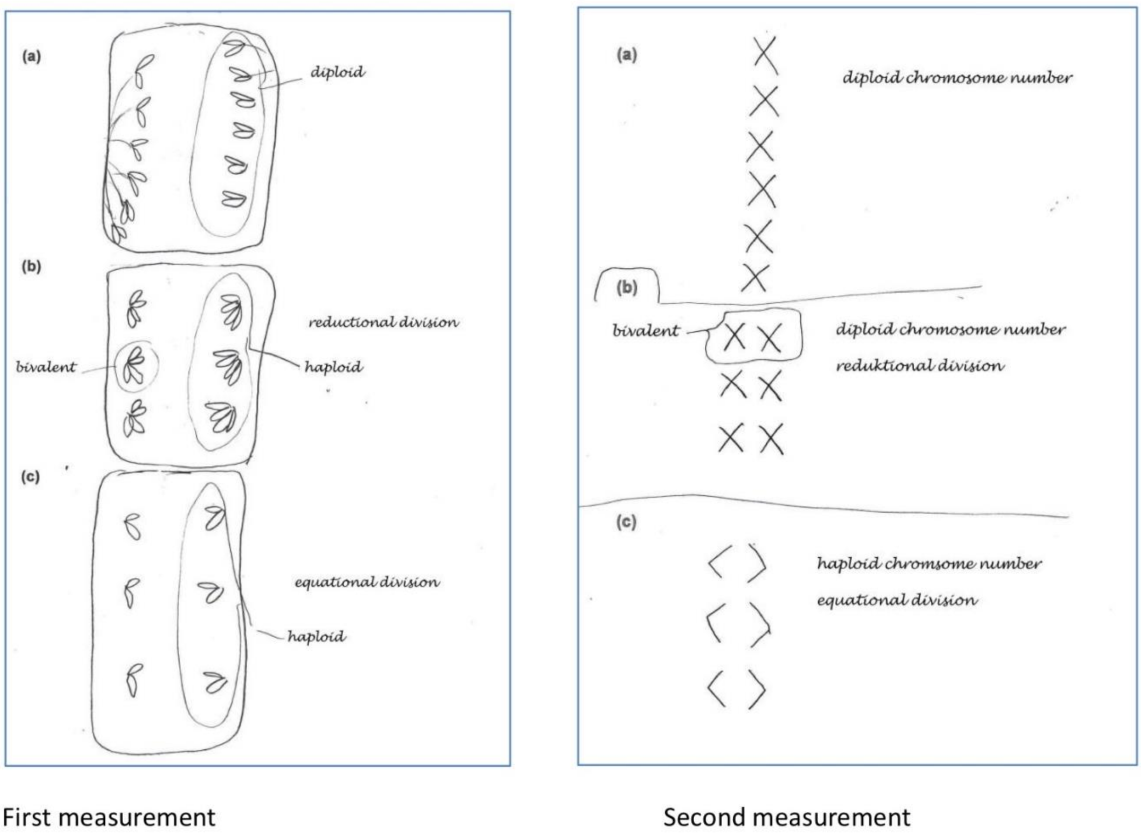
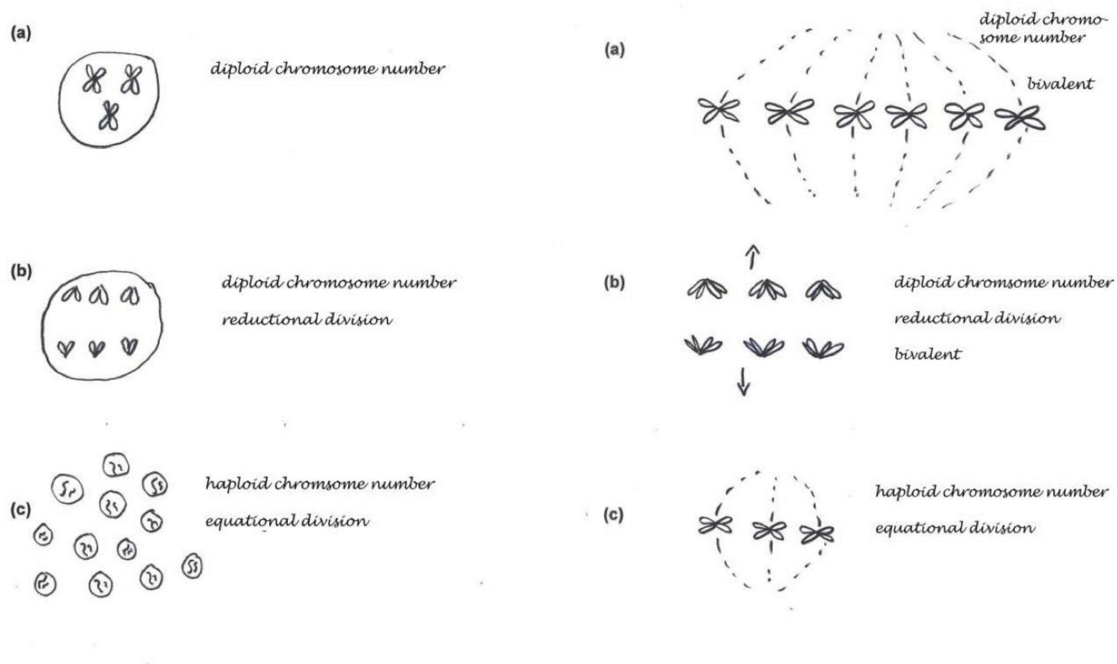


Figure 5. Example of a developed situation (student EMaj2).

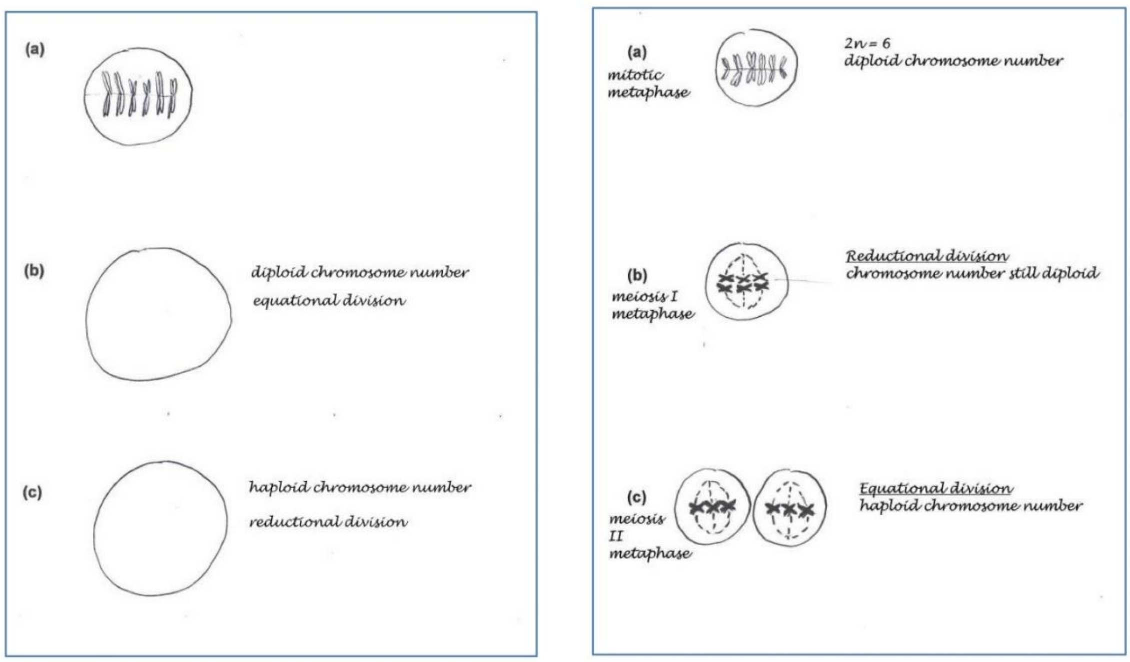
The drawings also showed development in concept recognition, e.g. with respect to the concept bivalent or haploidy and diploidy (Figure 5) or chromosome number (Figure 6). However, not all concepts were developed equally well, e.g. the concept of bivalent remainded obscure despite general development in concept recognition as in Figure 6, where 'bivalent' is apparently confused with the concept of a doubled chromosome. The understanding of the dynamic nature of chromosome structure and the fact that ploidy level is not coupled with the structural state of the chromosome (undoubled or doubled) is essential for understanding the concepts haploid and diploid. Furthermore, it is crucial to understand that meiotic phases are sequential and that the number of chromosomes, bivalents or daughter chromosomes in a certain phase result from the preceding phase according to the behavior and dynamics of chromosomes.

Misconceptions concerning the concept 'bivalent' decreased in the Measurement 2 (Table 1.), but based on frequent mistakes in chromosome number at metaphase I one gets the impression that development in concept recognition in this respect is only superficial. This topic needs to be investigated further. It might reflect the fact that especially the first meiotic division is in many ways much more complicated than mitotic division or the second meiotic division and many concepts are connected to the first meiotic division only, including the concept of bivalent. However, the unique events taking place under the first meiotic division are behind important genetic phenomena such as sex-linked inheritance or linkage, as well as the formation of haploid sex cells.



First measurement Second measurement

Figure 6. Example of a developed situation (student EMaj3).



First measurement Second measurement

Figure 7. Example of dramatic development (student EMaj4).

Effect of the activating task: comparing experimental and control groups. The analyses of students' drawings clearly showed that there was variation in students' conceptions of meiosis and that some progress has taken place during the instruction. The second aim of this study was to see if the experimental group who accomplished the activating task supporting metaconceptual awareness in the beginning of the laboratory working session outperformed the control group that received traditional instruction. Table 2 clearly shows that the experimental group benefited from the activating task. Their performance in the Measurement 2 was clearly better than the control group's performance. In fact, the control groups' performance was at the same level as the experimental groups' performance before the activating task. This suggests that traditional teaching is not very efficient in equipping students with a deep understanding of the concept of meiosis.

Table 2 Comparison of scores in experimental and control groups (maximum is 15 points).

Group	*n*	*First mearsurement* *M/SD*	*Second measurement* *M/SD*
Experimental group			
Biology major students	33	7.99 / 4.31	12.62 / 3.22
Minor students	8	5.00 / 5.78	6.88 / 6.22
All students	41	7.40 / 4.71	11.50 / 4.52
Control group			
Biology major students	25		8.94 / 4.32
Minor students	16		5.06 / 5.06
All students	41		7.43 / 4.97

In addition to the group comparisons, the impact of the activating task on the experimental group's learning was tested with paired-samples t-test to study change in performance at the individual level. Test scores of individual students were found to be significantly higher in the Measurement 2 than in the Measurement 1 ($t = 6{,}980$, $df = 40$, $p < .001$). Due to the abnormal distribution in the Measurement 2, the result was confirmed with a non-parametric test (relates samples Wilcoxon signed rank test), which gave the same result.

Discussion

The starting point for this quasi-experimental study was the notion that university students have difficulties learning the concept of meiosis (see also Dikmenli, 2010; Newman et al., 2012; Quinn et al., 2009). In addition, it was suggested that the students' conception of meiosis is at an insufficient level even after taking a course of it at the university. Meiosis is one of the most central concepts in biology and in genetics (e.g. Quinn et al., 2009), so students should understand it well if they are to progress in learning biology. The hypothesis of this study proposed that teaching with traditional lectures and laboratory working sessions may not be the best way to teach this difficult concept. Thus, a novel teaching method, based on a drawing task where students were supposed to draw the stages of meiosis and place given concepts of meiosis to their drawing was innovated. The teaching method also included a discussion where the correct solution was presented and the typical misconceptions and reasons for them were discussed. The aim of this task was to produce a cognitive conflict and awake metaconceptual awareness in students which would help them to understand their own initial conceptions of meiosis and develop it towards the scientific conception. Thus, the main goals of this study were twofold: to discover which kinds of challenges university students have concerning understanding the complex content of meiosis, and whether an easily applicable activating task, which was aimed at cognitive conflict and conceptual change, can assist students in learning the concept of meiosis better than the traditional laboratory working sessions alone.

Analyses of the students' first-round drawings showed that students really had a number of misconceptions concerning meiosis. The most typical of these were connected to the concepts haploidy and diploidy, chromosome number, bivalent and even chromosome itself. This is in line with the previous studies, which showed that students do not have only one specific problem, but multiple problems connected to understanding meiosis (Dikmenli, 2010; Newman et al. 2012; Wright & Newman, 2011). In addition, the expected result that most critical misconceptions and deficiencies in students' answers were related to the first meiotic division, is a finding that should be considered more seriously in order to advance biology education at different educational levels.Although students seemed to possess some factual knowledge about the concepts, the process of meiosis in its entirety was not understood well (cf. Newman et al. 2012).

When comparing the results between the experimental and control groups, it became evident that the experimental group students had a significantly better understanding of meiosis than the control group at the end of the laboratory working period. The students who were in the experimental group received higher scores on the task at the end of the period, i.e. they were able to produce better pictures with more correct concept placements than at the beginning of the course. An interesting finding was that the control group members' performance was at the same level than the experimental groups' performance before the activating task, although the course was ending at that time! This suggests that traditional teaching is not very efficient in equipping students with a deep understanding of the concept of meiosis. Furthermore, as expected, the students majoring in biology outperformed in both experimental and control groups in each measurement point, but the activating drawing task supported also minor students' learning effectively. Based on these results, it seems to be crucial that students are challenged to deeply consider their previous conceptions before the instruction and these prior conceptions are actively discussed in classrooms. Different self-explanation protocols, where students verbally open and discuss about their conceptions, often support students' learning effectively also according to previous studies (see e.g. Roy & Chi, 2005). In addition, co-activation, which in this study means paralleling the metaphases of mitosis and meiosis, results in activation of both processes in student's working memory simultaneously, which again may have supported noticing typical misconceptions (see also Kendeou & van den Broek, 2007).

These findings suggest that teaching of meiosis in university level should be organised in a way that enhances students' metaconceptual awareness and thus guides them to better understand the scientific concept. These notions should have implications for higher education also generally, since the main barrier to learning is not what the student lacks, but actually, what the student has i.e. prior conceptions (Carey, 2000). In this particular case, prior knowledge may strongly link to the knowledge of the "normal" cell division, namely mitosis, which again may result in mixing up the different processes of mitosis and meiosis.

Limitations of the study. The limitation of this study concerns the quasi-experimental design, which does not allow us to infer the results as in a true experimental design. Although we aimed at random groups, and there were no differences in in the previous study success between groups, the setting is a non-equivalent control group design, since we cannot guarantee the groups to be similar. Furthermore, the data were collected from one Finnish university, and further studies in different cultures should be conducted. Lastly, a delayed post-test would have offered information on how persistent the changes in participants' understanding were.

Conclusions. On the basis of the results of this study, we conclude that an activating drawing task which is aimed at cognitive conflict and fostering metaconceptual awareness, combined with traditional laboratory working sessions, assists students in developing a more scientifically sound conceptualization of meiosis as opposed to attending only traditional laboratory working sessions. The pedagogical implication of this study thus is that traditional teaching of the concept of meiosis can be much improved with a simple and not too much time-consuming task that is well designed and aims at deep discussion and conceptual development through cognitive conflict and awaking of students' metaconceptual awareness. Generally, science instructors at university should be aware of the fact that students bring to learning situations both their relevant and irrelevant prior knowledge, which may hinder learning (see also Carey, 2000; Smith & Kindfield, 1999). Therefore, it is crucial to develop instruction and tasks that support students to notice their existing misconceptions and foster their metaconceptual awareness to reach a conceptual change.

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