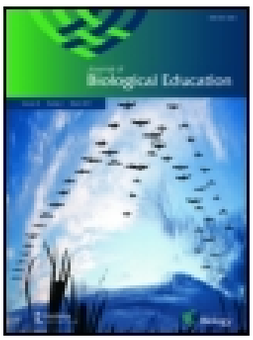

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Conceptions of meiosis: misunderstandings among university students and errors

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ABSTRACT

We have designed and tested an exercise to detect misconceptions among students about meiosis, a fundamental concept in genetics. A total of 30 students responded to a questionnaire, all of whom were in the fifth semester of the Biology bachelor's degree program offered by the Faculty of Science of the National Autonomous University of Mexico. Our analysis showed that students have a poor understanding of the fundamental processes of meiosis and that they have trouble distinguishing them. When asked to diagram part of the process, none were able to produce a complete and accurate representation.

KEYWORDS

Meiosis; misunderstandings; university students

Introduction

Student difficulties with genetics

The teaching and learning of genetics have been the object of frequent research in the field of Science Teaching Methodology over the last few decades (Figini and De Micheli 2005). In particular, Caballero Armenta (2008) observed that when students tackle new content, they do not start from scratch; they have already assimilated some information from different sources, but it rarely agrees with more accurate study materials.

Research studies have shown that learning individual topics in genetics does not contribute significantly to the overall understanding of the field; genetics is still scarcely understood, despite being widely included in various educational programs (for example, Kargbo, Hobbs, and Erickson 1980; Longden 1982). There may be various reasons for this situation, including the complexity of genetics concepts, alternative understandings, different types of knowledge, student reasoning modes, teaching strategies being developed, and textbooks. Textbooks in particular are outstanding curriculum materials because they mediate knowledge building; however, they can also be the source of student misunderstandings (Banet and Ayuso 1995; Cho, Kahle, and Nordland 1985; Figini and De Micheli 2005; Gimeno Sacristán (1991) 1994; Wood-Robinson et al. 1998). Knowledge of genetics is important because it is fundamental to understanding both the theory of evolution and familiar phenotypic relations, among other concepts. Therefore, it is not only necessary to determine the basis for student

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difficulties in this field, but also to propose breakthrough methodologies in teaching it (Caballero et al. 1997; Kuhn 1971).

Many students have difficulties understanding the process of meiosis, which frequently leads to errors (Brown 1990; Dikmenli 2010; Kalas et al. 2013; Kindfield 1991; Longden 1982; Newman, Catavero, and Wright 2012). For example, Dikmenli (2010) studied a cohort of 124 student teachers who were studying to become secondary school biology teachers at the Faculty of Education in Selcuk University in Turkey, and found that 54% made mistakes in preparing a diagram of meiosis. The students in this cohort had an average age of 22.3 years, with a range of 21–25 years. If students understand chromosomal behaviour during meiosis, they should be in a better position to understand Mendelian inheritance (Mertens 1992). Research on the teaching of genetics has focused on two issues, namely the incorrect assimilation and usage of genetics concepts, and the difficulties of solving genetics problems and exercises (Caballero Armenta 2008; Newman, Catavero, and Wright 2012). A great deal of research has studied the reasons for why secondary school students understand biological inheritance in a way that is inconsistent with what has been determined through scientific research (Ayuso and Banet 2002; Ayuso, Banet, and Abellán 1996; Ibáñez Orcajo and Martínez Aznar 2005; Martinez Aznar and Ibáñez Orcajo 2006).

This paper will analyse possible sources of the difficulties that undergraduate students have in understanding the process of meiosis, difficulties that can be observed in their own conceptions of the process.

The experience and the subjects

Students commit clear conceptual errors when detailing the steps following cell division, particularly in the case of meiosis. Such errors are so deeply ingrained that it has often been virtually impossible to eliminate them through the theoretical and practical classes related to genetics that were regularly offered at the universities in which we are or were teachers. A sampling of courses from our universities shows that they dedicate 11 to 18% of their time to studying mitosis, meiosis, and chromosomal rearrangements. The time devoted to these subjects includes theoretical explanations, exercises and problem solving, and laboratory activities involving the microscopic observation of samples in different stages of cellular division (Genética 2017; Genética General 2016; Genética I 2016).

Misconceptions about cell division are extremely problematic when they interfere with the analysis of chromosome alterations or preparations for genetic toxicology. These misunderstandings become apparent when students are tasked with diagramming the various division phases. In the literature, mitosis and meiosis have been addressed in two well-defined yet distinct manners: on the one hand, from a scientific point of view, research has focused on those molecules that participate in the division; on the other hand, the outcome of scientific advances was introduced in a simplified way or even distorted in teaching on many occasions, with the goal of making the material more understandable (Cajas 2001; Chevallard 1998). One approach to studying student understanding of biological processes has been to use drawings (Ben-Zvi Assaraf and Orion 2005; Dikmenli 2010). This qualitative research paper analyses drawings made by UNAM university students of the course of Genetics of the fifth semester in the degree in biology, in order to identify the incorrect accounts they put forward in explaining the location and transmission of hereditary information, accounts that hamper their comprehension of the chromosome theory related to inheritance. A previous study from Argentina devoted to this issue in other aspects of genetics was developed by Corbacho and De (2009).

In this study, a problem was provided for completion at home to 30 students studying genetics at UNAM. Each student was asked to complete it separately, using and citing whichever sources they considered most appropriate. Each participant was identified with a number. Each student was signed a consent in which he was informed about the use of the results of his production.

The problem given to the students is as follows:

Consider a $2n = 6$.

In one pair of homologous chromosomes, one of the members presents an interstitial knob. In another pair, one of the members possesses a satellite in terminal position. Finally, in another pair, one of the chromosomes presents a terminally heterochromatic segment.

Make a diagram of the following stages of mitosis and meiosis:

(a) pachytene, (b) mitotic metaphase, (c) meiosis metaphase I, (d) meiosis metaphase II, (e) mitotic anaphase, (f) meiosis anaphase I (draw one of the possible arrangements and indicate what probability it has to occur), and (g) meiosis anaphase II.

The students were given eight days to solve the problem. The results were digitized to facilitate their analysis and synthesized in Supplementary material Table 1. The data were parametrised by chromosome or bivalent morphology (depending on the stage), internal coherence of the diagrams in the different phases, and quality and quantity of the information provided in the diagrams compared to current scientific understanding of mitosis and meiosis.

Based on our hypothesis, we prepared two schemes in advance: (1) a prediction of what the pupils would draw, including potential errors (Supplementary material A), and (Figure 1) drawings following the actual process of meiosis, as observed in DAPI-stained (4',6-diamine-2-phenylindole, Figure 1) cytogenetic preparations. All images are in line with the meiosis of *Polybetes pythagoricus* (Sparassidae, Arachnida) (Figures 1 and 2 and see Supplementary material C), except the image in Supplementary material B, which outlines the meiosis of *Lycosa pampeana* (Lycosidae, Arachnida) stained with propionic haematoxylin. Both species have acrocentric chromosomes (Chemisquy et al. 2008; Rodríguez-Gil et al. 2007). The images were obtained at a magnification of 1000 × using a Leica LMDB optical microscope.

Results

Pachytene (Figure 2(a–g))

The schemes presented by the students contain several conceptual errors of different levels of relevance. One of the most important is that chromosomes are already shown as condensed throughout the process (Figure 2(c, d, f, g)). In all cases, metacentric or sub-metacentric chromosomes are observed, with a clearly defined centromeric region (Figure 2(c–g)). The students drew the condensed chromosomes using the same scheme that they used to represent mitotic metaphase in humans.

The second error is that the chromosomes are located alongside each other (Figure 2(d, e, g)) (78.57%) or one on top of the other (Figure 2(f)) (7.14%). In addition, several schemes show the chromosomes with one or two points of contact (Figure 2(e)) (32.14%), presumably based on the idea of DNA exchange between homologous molecules. In some schemes, the chromosomes have exchanged parts of their chromatids, as represented by colour differences between the homologs (Figure 2(g)). The problem with this is that the colour change could be interpreted as a physical change of place, as if there were a translocation between chromosomes; the implication from this is that an entire part of the genome moves, which is false.

We also found that there is a lack of internal coherence in the schemes. For example, in some cases the DNA molecules are represented as fine strands, separated from one another by a clearly marked centromere, while later on they are shown as thick paired lines, a closer representation of reality (Figure 2(e)).

In all the analysed cases, save for one, the sister chromatids are separated and distant; however, in reality, they are very close, given that they are linked by the cohesins.

Metaphase I (Figure 2(h–k))

The provided schemes present chromosomes with similar morphologies to those found in human C-mitosis. This state was defined according to Levan (1938) as the compactation degree maximum obtained in the chromosomes when the cell arrive to Metaphase, and the division is arrested, in an

Table 1. Answers from students at each stage.

		It correctly represents the chromosomes in:																												The students obtain correctly the probability of possible ordering of the chromosomes in the anaphase of meiosis	
		It correctly diagrmas the homologous chromosomes		Recognize the type of chromosome morphology?		Pachytene		Chromosomes location			Mitotic metaphase		Meiotic Metaphase I			Meiotic Metaphase II				Mitotic Anaphase		Meiotic Anaphase I				Anaphase II					
Case	2n: is the same in all stages?	Yes	No	Yes	No	Yes	No	Side by side	Topped	Yes	No	Yes	No	Chromatids interchange	Yes	No	Draw three chromosomes	Draw six chromosomes	Heteromorphic morphology	Yes	No	Yes	No	Migration mode		Yes	No	Yes	No	Yes	No
1	N		x		x		x	x			x		x			x			x		x	x		x		x			x
2	N		x		x	x		x			x		x	x		x			x		x		x	x		x				
3	N		x		x		x	x			x		x	x			x		x	x			x	x		x				
4	Y	x		x			x	x			x		x	x	x		x		x	x			x			x				
5	N		x		x		x	x			x		x	x		x	x		x		x		x	x		x				
6	N			x			x	x			x		x	x		x	x		x		x		x	x		x				
7	Y		x	x			x	x			x		x	x		x		x	x	x			x	x		x	x			
8	Y	x		x			x	x			x		x	x	x		x		x	x		x				x				
9	N		x		x	x			x		x		x			x			x	x			x			x				
10	Y	x			x		x	x			x		x	x		x		x	x	x			x	x		x				
11	N		x	x	x	x		x			x		x			x	x		x		x		x		x					
12	Y		x	x			x	x			x		x	x	x		x		x			x		x	x					
13	Y		x	x			x	x			x		x			x		x	x	x			x	x		x				
14	Y		x	x			x	x			x		x			x	x		x		x		x	x		x			x	
15	DK/NA		x	x			x	x			x		x	x		x		x	x	x		x		x		x	x			
16	N		x		x		x	x			x		x			x		x	x		x		x			x				
17	N		x		x		x				x		x			x					x		x	x		x			x	
18	Y		x	x			x				x		x			x	x		x		x		x			x			x	
19	Y		x		x		x	x			x		x			x	x		x	x		x			x					
20	N		n		x		x				x		x			x		x	x		x		x	x		x				
21	Y		x	x			x	x			x	x		x	x		x		x	x		x			x					
22	N		x	x			x	x			x		x			x			x		x		x	x		x				
23	N		X	x			x	x			x		x	x		x	x		x		x		x			x				
24	DK/NA						x				x	x				x				x			x			x				
25	N		x	x			x				x		x			x		x	x		x		x	x		x				
26	N		x		x		x	x			x		x			x			x		x		x			x				
27	N		x		x		x	x			x		x		x				x		x		x			x				
28	Y		x		x		x	x			x		x			x	x		x		x	x				x				
29	N						x	x			x		x		x		x		x		x		x		x					
30	N		x		x		x	x			X		x		x		x		x		x	x		x	x					x	

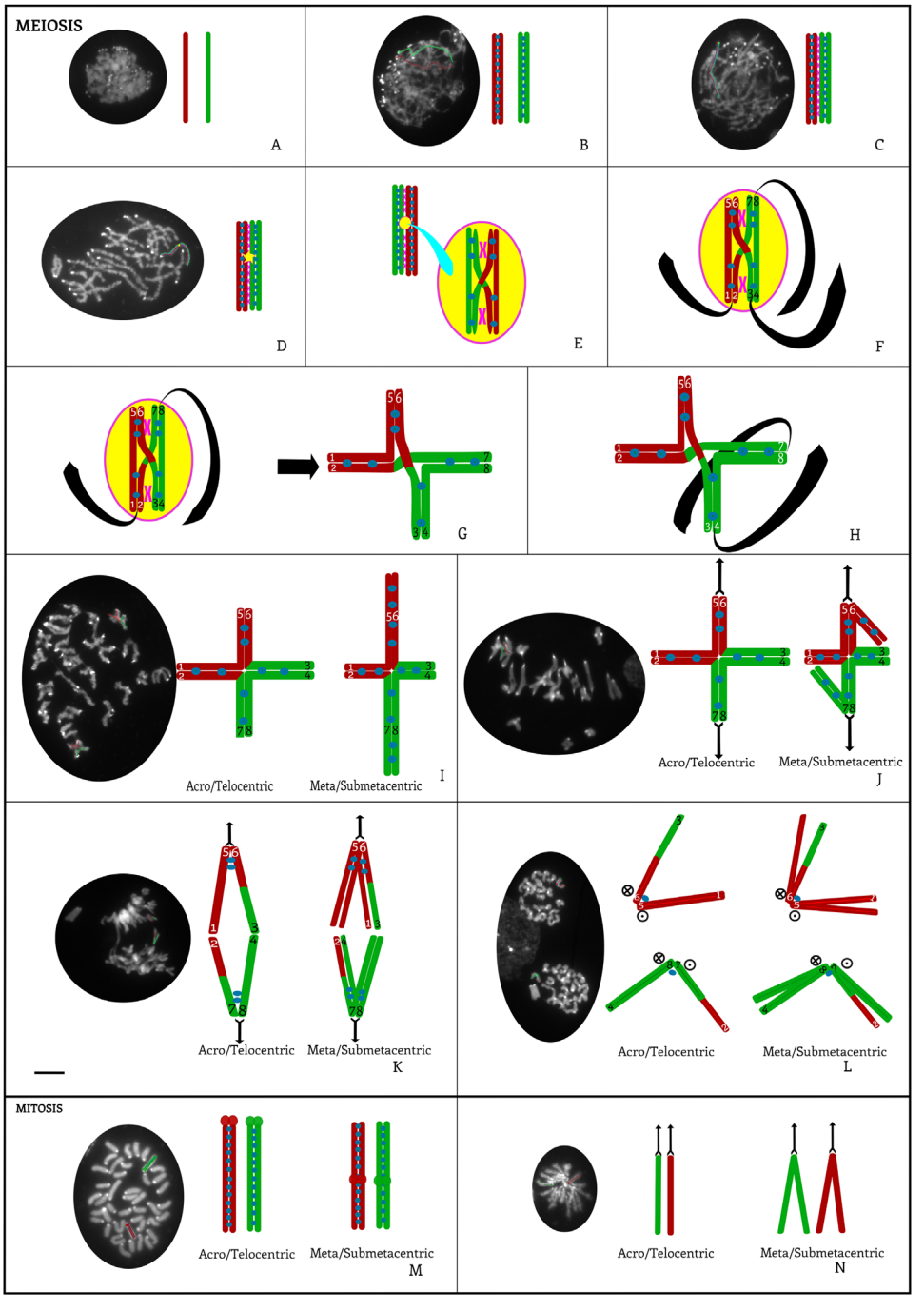

Figure 1. Images of *Polybetes pythagoricus* meiosis and accurate representations of different stages. In A–H, the representation is identical for any chromosome morphology. In I–N, the chromosome morphology influences the interpretation of the figure of the bivalent/chromosome. On the left the representation of acro/telocentric chromosome figures corresponding to the photograph and on the right the representation that should have been seen if the chromosome had been meta /submetacentric. (a) Interphase, (b) G2 (period after synthesis), (c) Early Pachytene, (d) Late Pachytene, (e) The site of the recombination nodule where crosslinking occurred, (f) The three movements involving chiasma rotation, (g) The telomeres involved in the first two movements of chiasma rotation, (h) The last movement of chiasma rotation and the telomeres involved, (i) Diakinesis, (j) Metaphase I, (k) Anaphase I (equatorial view), (l) Metaphase II (polar view), (m) Mitotic Prophase, (n) Pole of Mitotic Anaphase. The circled cross indicates the back of the image, while the point in the circle indicates the front of the image. Scale: 10 µm.

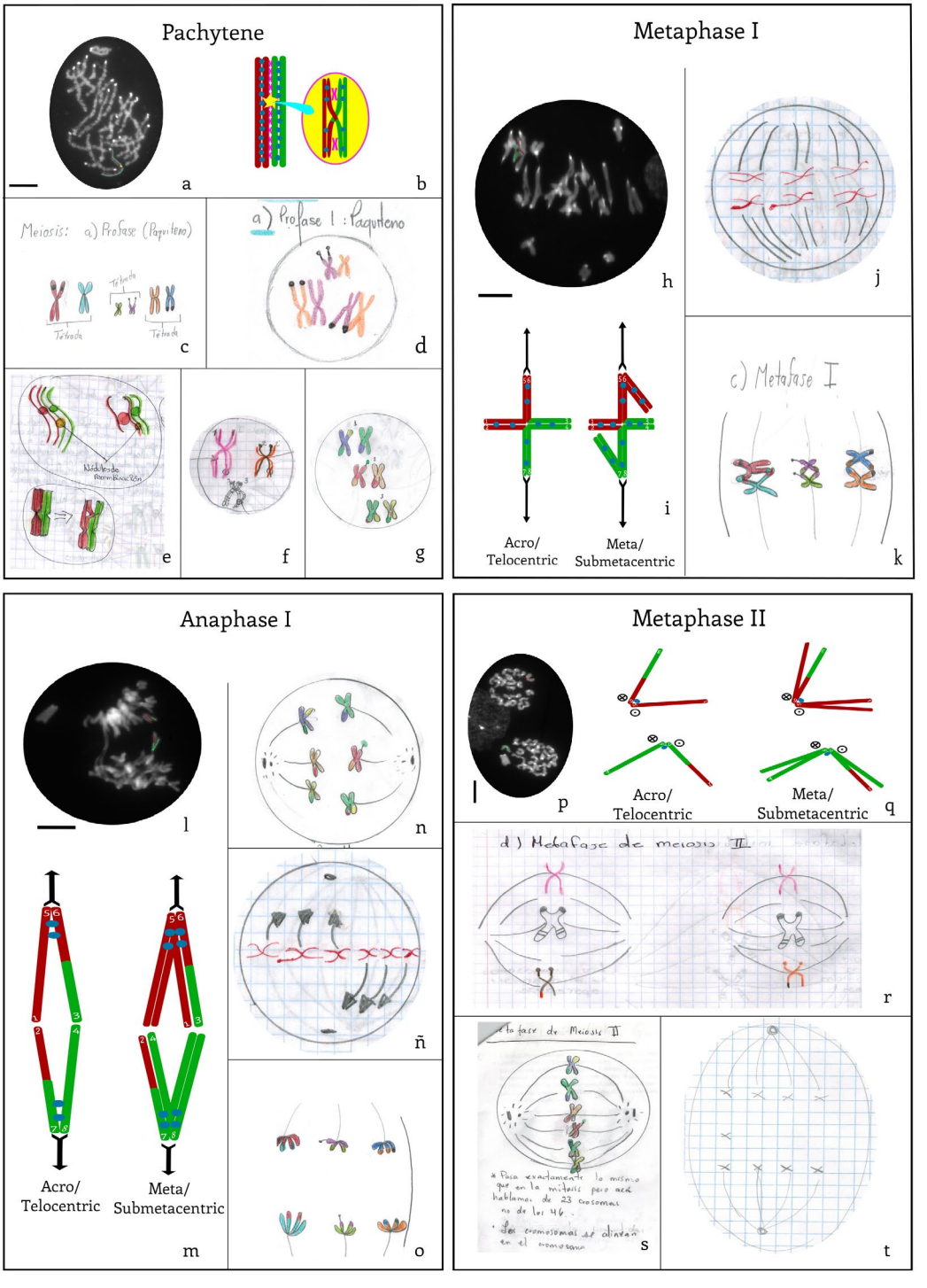

Figure 2. (a) Late Pachytene for *Polybetes pythagoricus*; (b) The site of the recombination nodule where cross-linking occurred; (c-g) Student schemes; (h) Metaphase I for *Polybetes pythagoricus*; (i) Bivalent in Metaphase I; (j-k) Student schemes; (l) Anaphase I for *Polybetes pythagoricus*; (m) Bivalent in Anaphase II; (n-o) Student schemes; (p) Metaphase II for *Polybetes pythagoricus*; (q) Bivalent in Metaphase II. (r–t) Student schemes. Scale: 10 µm. The cross in the circle indicates that the centromere will move backwards from the image, while the point in the circle indicates that the centromere will move towards the front of the image.

artificially induced abortive nuclear division as that caused by exposure in a human cell culture supplemented with a chemical agent that prevents the formation of the mitotic spindle (such as colchicine or 8-hydroxyquinone, among others). This allows the chromosomes to reach their maximum degree of condensation while not being located on the equatorial plate.

The chromosomes are shown parallel to the equatorial plate (Figure 2(j, k)). In this regard, they can be divided into two groups: (1) those that present both chromosomes separated, with their longitudinal axis parallel to the equator (Figure 2(j)), and (2) those whose homolog also has its longitudinal axis parallel to the equator, but with contact on both ends (Figure 2(k)). Homologous chromosomes, in some cases (39.28%), exhibit an exchange of DNA at their ends between one of the sister chromatids of each of the homologs (Figure 2(k)). In addition, there is no tension between the centromere and the poles (Figure 2(j, k)). The chromosomes present at most two exchanges and are always distal-terminals (Figure 2(k)). In all cases, sister chromatids are schematized separately and distant from each other (Figure 2(j, k)).

Anaphase I (Figure 2(l–o))

Again, the chromosomes are shown with similar morphologies to those found in human C-mitosis. There are cases where the chromosomes are separated evenly between the two hemispheres (Figure 2(n, o)). In addition, they generally migrate parallel to the equator (Figure 2(n, ñ)) (57.4%). A minimum number of students placed all chromosomes on the equatorial plate and indicated migration towards the poles using arrows (Figure 2(ñ)). Only one drew chromosomes pulled toward the pole at the centromere (Figure 2(o)). All students used a single spindle strand to represent a chromosome. In general, the heteromorphic character of the chromosomes was minimized or absent (Figure 2(n–o)).

Metaphase II (Figure 2(p–t))

Again, the chromosomes are shown with morphologies similar to those in human C-mitosis. Three types of errors were observed: in 50% of the erroneous cases, three chromosomes (Figure 2(r)) were shown; in 25%, six were shown (Figure 2(s) and in the remainder 25%, four chromosomes were shown, each represented by the letter 'X', for which no fine detail was provided (Figure 2(t)). The heteromorphic morphology of the homolog pairs was ignored in most of the schemes (96.43%).

Anaphase II (see Supplementary material B 1–8)

Several types of diagrams were provided with a homogenous distribution. In this stage, three chromosomes are pulled from the centromere, migrating to each pole. In some cases the centromeres are ahead of the line of the chromosome arms, while in others, the centromeres are behind, as if they were pushing the chromatids (see Supplementary material B (3, 4, 6–8)). In one case, the chromosomes were pulled not by the centromere, but by a telomere (see Supplementary material B (5)).

Instead of three chromosomes towards each pole, some students drew four or six (see Supplementary material B (6)). In all but one case, one chromatid was drawn per chromosome. However, in the remaining one, two chromatids per chromosome were outlined, with one chromosome heading toward one pole and nothing towards the other. In this case, both chromatids migrate rigidly.

Mitotic metaphase (see Supplementary material C (1, 3, 5)

All schemes represented metacentric chromosomes, similar to those observed in human C-mitosis (see Supplementary material C (3)). In total, six students (20.68%) did not use the requested number of chromosomes.

Mitotic anaphase (see Supplementary material C (2, 4, 6)

Schemes represent a chromatid with a medial centromere. The angle that the chromosomes take give them a 'V' shape. Most of the schemes present the centromere in front of the chromatid line (see Supplementary material C (4)). Only

two students represented this stage differently. One of the students placed the centromere behind the chromatid line (see Supplementary material C (5)). The other student showed the chromosomes pulled by the telomeres; however, the scheme seemed to present a centromere in the middle of each molecule of DNA represented with a break (see Supplementary material C (6)), in this scheme can be observed that mitotic anaphase is reductional

Internal inconsistencies and conceptual errors (Figure 3(a–g))

Each student represented mitotic metaphase and metaphase II (Figure 3(a)) as identical, as well as mitotic anaphase and anaphase I (Figure 3(b–d)). Students consistently showed an increased number of chromosomes in metaphase II when compared to the number of chromosomes that migrate to each pole in anaphase I (Figure 3(e)).

Five (17.86%) students failed to correctly interpret the 2n in the problem. One showed eight chromosomes in mitotic metaphase; two showed three in mitotic metaphase and six in meiosis; one showed four in mitotic metaphase and two homologs in meiosis, except for four chromosomes in metaphase II; and one changed the number of chromosomes three times (Figure 3(f, g)).

Chromosomal descriptions (for example, as knobs, satellites, and exhibiting positive heteropyknosis) were limited to a handful of stages; no students provided said identification in all stages. Those students that incorporated this information only marked it for one of the two chromatids. In some cases, both homologous chromosomes presented a chromatid of each type (Figures 2, 3 and see Supplementary material B and Supplementary material C).

Most schemes where the achromatic spindle was joined to the chromosome represented it as a single spindle strand bound to the centromere (Figures 2(h–k, n–o, r–t); 3(a–g) and see Supplementary material B (5–8) and see Supplementary material C (3–6)). In many cases, the spindle did not touch the chromosomes. Only one student drew more than one strand (Figure 2(i)).

One student showed metacentric chromosomes pulled by the telomeres in both mitotic and meiotic anaphase; however, different telomeres were used for each pole (see Supplementary material B (5) and Supplementary material C (8)).

Discussion

As early as 2010, Dikmenli used drawings made by biology student teachers to study their misconceptions about cell division processes. As in his work, we found errors in the requested schemes, presumably based on the literature they consulted. The drawings by the students were identical to those found in books and internet sources recommended by university courses in some way related to genetics; this applies even at universities with important research centres (see Supplementary material Table 2).

Simplified features in diagrams of meiosis and in their accompanying descriptions (when they exist) in the literature are noteworthy. Presumably, these simplifications are meant to make meiosis more understandable for students, regardless of their educational level. This simplification, engaged in as part of didactic transposition, results in misconceptions that become evident when students must explain and diagram the process (Cajas 2001). Even worse, these simplifications contain a series of graphical errors that are not treated as important, as these errors are not clarified in accompanying explanations.

The mistakes made by the students can be organized into several categories, namely:

(1) The use of the classic 'X'-shaped metacentric chromosome, as opposed to what is observed in a cytogenetic preparation with a microscope (Figure 1).
(2) Physical exchange of portions of sister chromatids between homologous chromosomes in prophase I (Figure 2 (g, j, k)).
(3) Incorrect orientation of the chromosomes and the physical position of the centromere in meiotic metaphase I and II and mitotic metaphase (Figures 2 (j, k); see Supplementary material B (4); and Supplementary material C).
(4) Not correctly indicating in which phases the chromosomes have one or two chromatids.

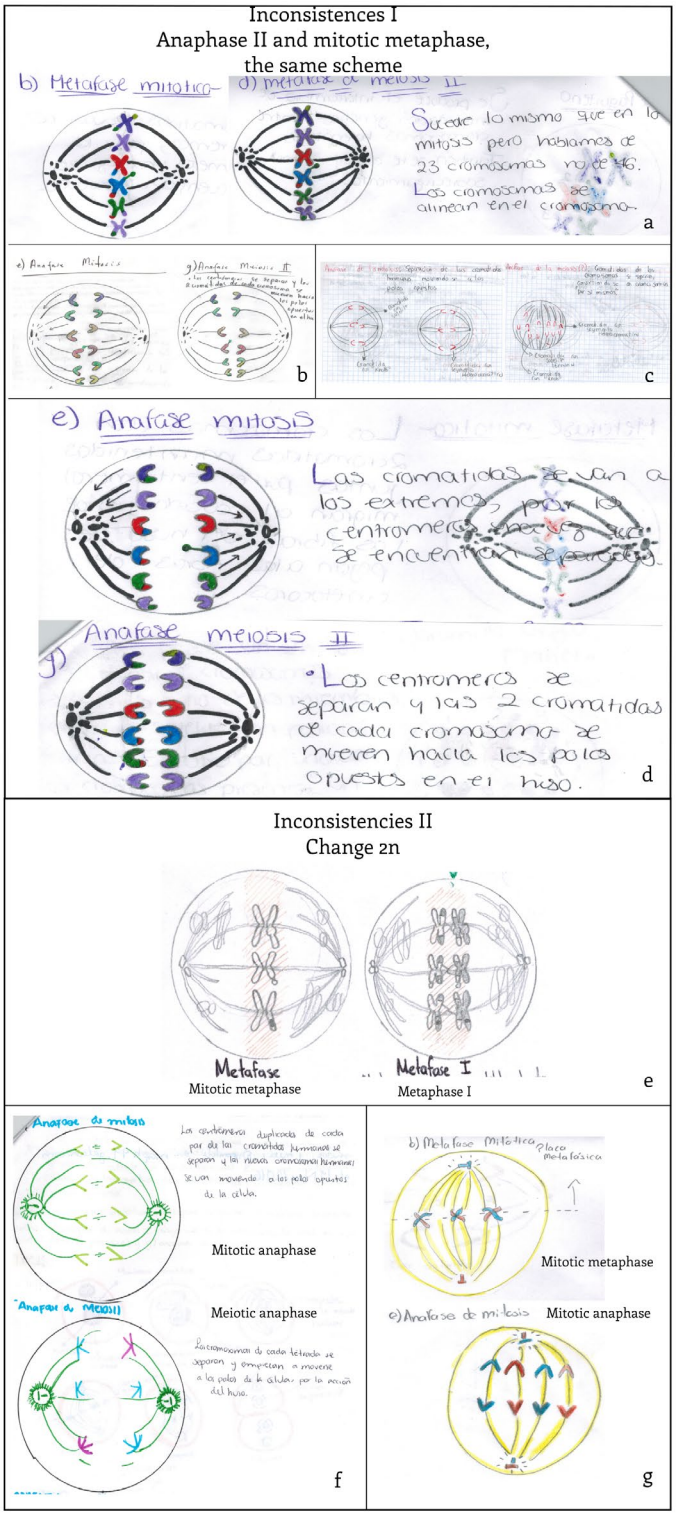

Figure 3. (a–d) The schemes from four students, showing that each gave identical images for Anaphase II and Mitotic Anaphase. (e–g) The schemes from three students, showing that each set had internal inconsistencies.

Table 2. Websites offered by Google search in image mode to the words 'meiosis' and 'cell division'. Pages that become unavailable after this paper is published can be accessed through the historical archives, available at www.archive.org.

Name	URL
la ciencia y sus demonios	http://cnho.wordpress.com/2009/08/07/el-huerto-evolutivo-3-raphanobrassica-la-cruz-de-karpechenko/
indiana university – departament of biology	http://www.biology.iupui.edu/biocourses/N100/2k4ch9meiosisnotes.html
sparknotes: sat subject test: biology test center basis of inheritance: meiosis	http://www.sparknotes.com/testprep/books/sat2/biology/chapter7section1.rhtml
natural history magazine	http://www.naturalhistorymag.com/biomechanics/112,082/breaking-point
sharonap-cellrepro-p3 - advanced topics in genetics and development project	http://sharonap-cellrepro-p3.wikispaces.com/Creating+Variation
cell division:mitosis & meiosis - video tutorial-watch online	https://web.archive.org/web/20,100,123,213,839/http://www.bioinformaticsweb.org/2009/02/cell-divisionmitosis-meiosis-video-tutorial-watch-online/
study.com	http://education-portal.com/academy/lesson/nondisjunction-in-meiosis-definition-examples-quiz.html#lesson
shutter stock	http://www.shutterstock.com/pic-116607409/stock-vector-vector-diagram-of-the-meiosis-phases.html
deconceptos.com	http://deconceptos.com/ciencias-naturales/meiosis
paw peds	http://pawpeds.com/pawacademy/genetics/genetics/thechromosomes_es-.html
bbc	http://www.bbc.co.uk/education/guides/zvb7hyc/revision/5
ventanas al universo	http://www.windows.ucar.edu/earth/Life/genetics_meiosis.sp.html
ba education uk	http://www.ba-education.com/for/science/dnabiology.html
epigenetica por fabio celnikier	https://web.archive.org/web/20,080,422,035,101/http://www.epigenetica.org/?page_id=186
fisicanet	http://www.fisicanet.com.ar/biologia/informacion_genetica/ap09_mitosis_vs_meiosis.php
profesorjano.org	https://web.archive.org/web/20,130,102,030,530/http://profesorjano.org/fisiologia-y-anatomia/genetica-molecular/
kansas state university	http://www.ksu.edu/biology/pob/genetics/defin.htm
malebolge	http://www.malebolge.net16.net/science10/main.html
the biology corner	http://www.biologycorner.com/worksheets/meiosis2.html
student's study guide	http://www.synapses.co.uk/genetics/ssg5.html
the free dictionary	http://medical-dictionary.thefreedictionary.com/meiosis
mechanisms of genome haploidization	http://www.meiosis-dfg.tu-dresden.de/
wikimedia commons	http://commons.wikimedia.org/wiki/File:Meiosis_diagram.jpg
pearson	http://www.phschool.com/science/biology_place/biocoach/meiosis/intro.html
art.com	http://www.art.com/products/p10317719-sa-i938015/meiosis.htm
national animal genome research program	https://web.archive.org/web/20,120,419,080,246/http://www.animalgenome.org/edu/genetics/mitosis.html
school of mathematical & computer sciences	http://www-users.york.ac.uk/~mal503/common/thesis/c3.html
the student doctor network	http://forums.studentdoctor.net/showthread.php?t=651,800
college of arts and science	http://www.bio.miami.edu/~cmallery/150/mitosis/c13x8meiosis-comparison.jpg
palaeos	https://web.archive.org/web/20,100,207,135,003/http://palaeos.com/Fungi/Lists/Glossary/Images/Meiosis.gif
biología	http://missmsoledad.wordpress.com/2008/06/06/segundo-medio-biologia/
national institute of general medical sciences	http://publications.nigms.nih.gov/thenewgenetics/chapter1.html
división celular : meiosis y reproducción sexual	https://web.archive.org/web/20,060,922,122,456/http://mail.efn.uncor.edu/dep/biologia/intrbiol/meiosis.htm
the biology corner	http://www.biologycorner.com/APbiology/inheritance/10–1_meiosis.html
pant cell biology by dr. g. r. kantharaj	http://plantcellbiology.masters.grkraj.org/html/Plant_Cell_Division1-Cell_Division.htm
radbound universiteit	http://www.vcbio.science.ru.nl/en/image-gallery/show/print/AN0098/
yale school of medicine	https://web.archive.org/web/20,050,729,073,730/http://info.med.yale.edu/genetics/ashley/

All the pages were accessed on 24th May of 2016

(5) Inconsistency in the number of chromatids and/or chromosomes between consecutive stages of meiosis (Figure 3(e–g).
(6) Identical schemes for mitosis and phase II of meiosis, in both cases including homologous chromatid exchange typical only of mitosis (Figure 3(a–d) and see Supplementary material C (3)).

Possible sources of errors

Regarding chromosome representation

The most viewed and studied chromosomes come from mitosis, specifically from human mitotic metaphases. Chromosomes are immobilized in metaphase using colchicine, which is responsible for the classic 'X'-shaped appearance. The largest human chromosomes, and therefore the most visible, are metacentric, explaining why that is how they are represented universally (Trask 2002). Saka et al. (2006) found problems in how biology student teachers and 8th, 9th, and 11th grade students in Turkey explained chromosomal behaviour.

Although our test was clear to mention that our students were working with a 2n diploid organism, two students consistently indicated the presence of 46 chromosomes or numbers related to the human ploidy in their explanatory texts, even if the diagrams themselves were accurate (Figure 3(a)).

The indicated chromatin exchange between homologous chromosomes in metaphase and mitotic anaphase could be due to the significant amount of bibliography indicating that the second phase of meiosis is mitotic, although without previous DNA duplication (Figure 3(a–d) and see Supplementary material C (4). Another error that is observed are mitotic anaphases with reduction of chromosome content, (see Supplementary material C (5)), possibly supported by the same concept that the anaphases of meiosis to mitosis are equal.

Regarding chromatid exchange

The observed errors are probably originally based on the diagrams in Chapter 3 of the book 'The Mechanism of Mendelian Heredity' (Morgan et al. (1915) 1957), in which one of the homologous chromosomes was represented as a black bar and the other as a connected series of white beads; these white beads were then shown to exchange, indicating complete DNA exchange. All schemes generated from this model to explain chromosomal exchange were identical or very similar to this representation, or else accompanies by the addition of sister chromatid duplication (see images from the websites mentioned in Supplementary material Table 2). However, since 1957, researchers have shown, in addition to other discoveries, that there are molecules that hold homologous chromatids together, others that link sister chromatids, and several that form part of the complex anchorage system that links the kinetochore to the spindle fibres (Jeffrey, Craig, and Choo 2005). These discoveries have never been integrated into educational materials for mitosis or meiosis. Even when cohesins are indicated, they are shown alongside mitotic chromosomes in C-mitosis and not similarly to how they actually appear (Cohésine 2017). This ignores the presence of the synaptonemal complex. In this study, none of the students rendered the cohesins and only one mentioned the synaptonemal complex. However, he must have felt unable to represent it in his schemes since he did not only fail to diagram it, but rather represented the homologous chromosomes as separated in the cell nucleus. The lack of knowledge of these molecules in the twenty-first century is responsible for the continued errors in schematics of mitosis and meiosis and the failure of students to incorporate new concepts.

Consequences of the errors

The conceptual errors in the outlines of the early stages (paquitene) propagate to the later ones,, for example, metaphase I is represented incorrectly, with two chromosomes in a C-mitosis shape paired and aligned to the equatorial plate, and with the longitudinal axis always parallel to the equatorial plane (Figure 2(j–k)) and in some cases not even a chiasmata is represented (Figure 2(c, g, j)). This conduce a that the chiasmata are always terminal, since it is impossible to draw proximal chiasmas on chromosomes with a C-mitosis shape (Figure 2 (d-f, k)). If the chiasmas are shown as terminal and there is no possibility of drawing one as proximal, it becomes very difficult for students to conceptualize the existence of bivalents with two or more cross-links on the same arm. Therefore, students interpreting actual images of them fail to understand them and draw them properly. Figures 2, 3(e–g), and see

Supplementary material C, show a photograph and a diagram of the meiosis of *Polybetes pythagoricus* from the literature and those drawn by the students. Another constant error that was observed is that centromeres almost never point to the poles, even though the metaphase is universally described as the moment in which the centromeres are already stretched towards the poles of the cell (Figures 2(j, ñ; r–t); 3 (a; e–g), see Supplementary material B (4) and Supplementary material C (3)).

Reindl et al. (2015) proposed that images and animations allow students to better understand theoretical concepts relating to phenomena that are not visible to the naked eye. However if the images and animations are not representative of what actually happens, they result in conceptual errors like those described.

Despite the errors in their schemes, the students were able to correctly solve mathematical problems relating to meiosis.

The provided data indicate that cell division and the resolution of heritability are two unconnected themes in the minds of students; on one hand, there is mathematics and problem resolution, and on the other, the biological cycle itself. Thus, genes are letters in a Punnett square, or in a probability tree, while chromosomes are spots under a microscope that are difficult to interpret. They do not think to allocate genes to them, and with much effort can hardly locate chromatids. The students solve Mendelian inheritance problems systematically, without considering that what constitutes that system is meiosis itself.

This dissociation could explain the confusion and misinterpretations in the meaning of specific genetics terminology such as gene, allele, character, locus, chromosome, and chromatid, and certain concepts such as the location of the alleles on the chromosomes, the difference between mitosis and meiosis, and the concepts of dominance and recessivity; these issues have been discussed by Collins and Stewart (1989), Brown (1990), Albaladejo and Lucas (1988), Moll and Allen (1987), Pashley (1994), Radford and Bird-Stewart (1982), Smith (1988), and Heim (1991), among others.

It can be concluded that understanding meiosis is not easy and that the figures and images available to students, in their attempt to simplify concepts, instead deny their importance and complicate understanding them. This largely coincides with conclusions reached by Radford and Bird-Stewart (1982). Cho, Kahle, and Nordland (1985) performed an error analysis that appeared in genetics and teaching textbooks. They concluded that one cause for these errors is the sequence in which topics are taught, and that another was the comprehension of meiosis. They argued that texts are the primary source of knowledge in the majority of biology classes at the secondary level, and that errors and omissions can prevent learning. In the same sense, we can argue that images available today on the internet to students of different educational levels contain a significant number of errors and omissions that could be the cause of difficulties for university students in understanding the cell cycles. By way of example in Supplementary material D (Rodriguez Arnaiz, Castañeda-Sortibrán, and Ordáz Téllez 2016) we leave indicated some of the most common errors that appear in the schemas of the bibliography.

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