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## **Solving a problem about cancer treatment: How does the use of the mitotic spindle model evolve during small group discussions?**

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## **Solving a problem about cancer treatment: How does the use of the mitotic spindle model evolve during small group discussions?**

Cell division is one of the most relevant processes in Biology, for instance, to understand the reproduction of species or the development of tumours. Learning this content requires not addressing it out of context but integrating it into real-life problems that demand students to apply cell division's knowledge. In this study, the authors examine how ten small groups of 10th grade students apply their mitosis models to solve a problem about cancer treatment; and how they progress in their application in terms of students' discursive moves. Throughout their discussions, learners must explain what happens to a treated tumour cell which cannot finish its division. To do so, they should consider understudied ideas such as the prometaphase's stage or the importance of bipolar spindle formation. Data collected are the groups audio recordings and their written reports. The results show that all groups handle notions, such as the need of centrosomes' duplication or microtubules-chromosomes' attachment for mitosis to be complete, throughout the activity. Although all groups integrate two or three ideas at a time into their discourse, none of them manage to combine and contextualise all the expected ones. Implications for Biology education are discussed.

Keywords: biology education, conceptions/ideas, discursive moves, mitosis, real-life problems, secondary school

### **INTRODUCTION**

Biology contents such as the regulation of the cell cycle or the cell division processes are very recurrent in Secondary Education curricula (Dikmenli 2010). An adequate knowledge of these micro-level concepts is essential for students' understanding of organisms' growth or reproduction, as well as pathologies such as cancer and the mechanism of action of its treatments (Domènech 2016). However, cell division is one of the most difficult contents to learn since the last century (Metzger and Yowler 2019; Öztap et al. 2003). Students show problems in modelling mitosis and meiosis as dynamic and continuous processes, or in recognizing subcellular structures at different stages in real images, despite having reference drawings and diagrams (Dikmenli 2010; Shelden et al. 2019). For instance, learners do not often consider stages such as the prometaphase,

which is even omitted in some textbooks (Esquivel-Martín et al. 2021; Orcos and Magreñán 2018).

Moreover, learners are often confused with cell division related-terms (Riemeier and Gropengießer 2008), such as centromeres-centrosomes-centrioles or chromatin-homologous chromosomes-sister chromatids, exchanging their roles or considering that they are essentially the same structure (Kalimuthu 2017). Besides, cell division has traditionally been addressed in terms of nuclear division and chromosomal dynamics (Esquivel-Martín et al. 2019; Kindfield 1991) although a comprehensive knowledge about this topic requires considering all the cell structures involved, and how they evolve along the process. For instance, when students are asked to freely draw the whole process or to identify mitosis and meiosis stages, most of them usually focus on chromatin condensation or karyokinesis, forgetting to represent structures such as centrosomes or spindle fibres (Dikmenli 2010).

These difficulties may be related to the capacity of abstraction required to handle the microscopic scale (Fernández and Jiménez-Tejada 2018), as well as to the use of archetypal models of cell division as references, such as simple diagrams, cartoons, or textbook charts. This kind of representations sometimes contain errors that do not conform to the reference model accepted by the scientific community, so they are often difficult to relate to micrographs (Shelden et al. 2019). To deal with these problems, although there are studies that explore students' conceptions about the status of the organelles involved in cell division at higher education levels (Yakışan 2013), there is a scarcity of research that addresses these topics in Secondary Education. Even though there are proposals that engage students in dramatizing the process of cell division by representing the role of different structures (Chinnici et al. 2004) or modelling them with objects such as chenille stems (Clark and Mathis 2000), the degree of depth and realism

of these approaches is not enough. Therefore, more research is needed on the challenges of applying notions such as the agents affecting the rate of mitotic cell division in real contexts (Metzger and Yowler 2019; Williams et al. 2012).

To prevent students from associating learning about cell division as something monotonous and disconnected from their lives, it is important to provide them with opportunities to solve real-life problems related to this topic, such as the environmental pollution effects on several species' reproduction. These dynamics are based on the use of contextualised open-questions without an obvious solution (Esquivel-Martín et al. 2021), contributing to making sense of scientific knowledge through its application, since both processes, the construction of notions and their application, are intertwined (Jiménez-Aleixandre and Reigosa 2006). Students' talks and actions can be used to analyse this meaning-making process (Chen 2019), which, according to the researchers, becomes even more important than the final solution. In this work, students should give at least two possible explanations about what happens to a treated tumour cell that cannot finish its mitosis. For this purpose, they should evaluate the available evidence (e.g., micrographs of different mitosis stages) and apply the mitotic spindle model, integrating complex ideas such as the cell cycle checkpoints.

Therefore, the research questions are: *how do students apply their ideas about mitosis to solve a problem related to cancer treatment?* and *how do they progress in the use of the mitosis model throughout the activity, in terms of students' discursive moves?*

## **METHODOLOGY**

### ***Participants***

Participants are two classes of 10th grade students ( $N_1=19$ ;  $N_2=19$ ) from a state high school in Madrid (Spain). Their teachers, 'Ms. Nadia' and 'Ms. Irina', have both degrees

in Biology and extensive teaching experience (more than ten years). Both classes belong to a bilingual strand, so Biology is taught in English, meaning that their cultural (and often economical) background is higher than average. Learners work in ten groups of 3-4 people (academic year 2019-20) encoded from the A to E in Ms. Irina's class and from F to J in Ms. Nadia's (students and teachers are identified with pseudonyms respecting their gender). Group members are chosen by the teachers to ensure heterogeneity in terms of learners' science achievement within each group. Regarding the level of prior life science education of the participants, the Spanish curriculum (Royal Decree 1105/2014) includes the study of cellular structure and function at lower educational levels, but the cell cycle and cell division processes are addressed in depth in 10th grade. Thus, before the intervention, each teacher has explained the cell division (mitosis and meiosis) in a theoretical way, using some archetypal images, mainly focusing on the level of chromatin condensation and/or not promoting the application of the knowledge in real contexts.

### ***Mitosis activity: 'The use of mitotic spindle'***

To understand the importance of statements like Rudolph Virchow's: *'all diseases are disturbances at the cellular level'*, the authors have designed and implemented a teaching sequence (Esquivel-Martín et al. 2021) that address different issues related to mitotic and meiotic divisions (Table 1). The designed problems require students to discuss their responses, mostly in groups, using both their cell division knowledge and the evidence provided by the teachers, such as written reports, data tables or micrographs of different subcellular structures in distinct cell cycle stages.

**Table 1. Summary of the teaching sequence**

Activity name	Related to...	Objective(s)
<i>1. The use of mitotic spindle</i>	Mitosis (use of anti-mitotic drugs for cancer treatment)	To apply the mitosis/mitotic spindle models to identify what is altered in a tumour cell after it has been treated (monopolar spindle), justifying why it cannot divide.

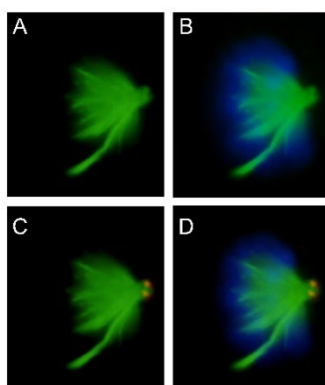
2. <i>It all depends on how you look at it</i>	Mitosis (treated or untreated tumour cell?)	To apply the spatial vision and the mitosis/mitotic spindle models to identify a metaphase (polar view) in a micrograph of a fictitious tumour cell, inferring whether the cell division process can be completed.
3. <i>'Meiostory'</i>	Meiosis (reproductive problems associated with environmental pollution)	To interpret different data sources, such as a map in a fictitious news story or a technical report on the problems arising from pesticide water pollution, to argue which city on the map is the most polluted and propose solutions on how to manage the situation.
4. <i>Hybrids: Origin of new species?</i>	Meiosis (infertility of hybrids such as the mule)	To argue why hybrids, such as the mule or the liger, are sterile by applying the meiosis models.

The first activity (Table 2), presented through a split video (storytelling: link blinded for review), consists of solving the fictitious case of a mother who has may discovered a cancer treatment by using carbamazepine. However, she does not know what is the drug's mechanism of action (at the cellular level) that is keeping the tumour from advancing. To solve the problem, students are required to: a. *model mitosis and meiosis through individual and group drawings and apply their models to identify mitotic stages in real images*; b. *use evidence provided by teachers to evaluate and modify their models*; and c. *apply their final models to identify what is altered in the tumour cell after treatment, discussing with their peers why it cannot divide*. In this study, the researchers only analyse the last phase of the activity, which focus on mitotic division (Table 2).

**Table 2.** Tasks' description for each phase (Ph) of the activity. The phase highlighted in grey is analysed in the present study.

Ph	Task
1	Individual application of prior knowledge about mitosis to solve the final question (before the intervention).
2	Expression of mitosis models (individual drawings). This representation helps students organise their ideas before engaging in the development of the group models.
3	Visualization of the first part of the video to introduce the meaning of the activity.
4	Representation of the consensual model of mitosis (group drawings) for students to externalise their thinking and discuss their ideas in a group.
5	Visualization of the second part of the video to focus the interest on mitotic spindle and centrioles.
6	Elaboration of the consensual model of mitotic spindle (group drawings).
7	Application of the group mitotic spindle models to identify different cell cycle stages in six microtubules' micrographs.
8	Evaluation of group mitotic spindle models after seeing ordered six micrographs of stained and labelled structures (chromatin, microtubules and centrioles) in different cell cycle stages.
9	Visualization of the third part of the video to present the problem through a treated tumour cell's micrograph (monopolar spindle).

In this phase, each group has a micrograph of the microtubules of a cell exposed to carbamazepine (Figure 1A) and should apply their theoretical models of mitotic spindle to explain why the cell cannot finish its mitosis. To test their hypotheses, students are expected to request additional data, such as micrographs of other stained and labelled structures (Figure 1B, Figure 1C, Figure 1D), in which they could check their presence/absence or disposition. As Bravo-Torija and Jiménez-Aleixandre (2017) recommend, they should interpret and integrate the new information in their justifications, coordinating the images with their theoretical models to evaluate which of their hypotheses is the most accurate.



**Figure 1.** Monopolar spindle with green-labelled microtubules (A). In picture B, chromatin (blue dye stained) and microtubules (green-labelled) are presented as a merged image. In picture C, microtubules (alpha-tubulin) are green-labelled, and centrosomes (gamma-tubulin) are orange-labelled (two centrioles per dot). The three structures merge in picture D. Cellular immunodetection and staining was carried out as described by Pérez-Martín et al. (2008).

### ***Reference response to the problem***

Under Spanish evaluation standards for the 10th grade, students should distinguish the different components of the cell and their functions, depending on the different cell cycle's stages (Royal Decree 1105/2014, p. 211).

Taking this into account, according to the authors, a reference response to the questions: *'Why can't the treated tumour cell in the image (Figure 1A) finish mitosis?'*



*What stage is the cell in?* ' should consider two possible hypotheses for what the students observe (Figure 1A).

The first one would be:

*The carbamazepine (drug) avoids the centrosomes duplication (duplication) at the S-phase of interphase (stages). The cell can pass the G2 checkpoint and start mitosis, because it only checks whether the genetic material has been duplicated. Then, from the only existing centrosome it polymerises (polymerisation) a monopolar spindle that interacts with the chromosomes (attachment) at prometaphase (prometaphase), when the nuclear envelope fully disappears, but it is unable to bi-orientate and congress them to the equatorial plate. This prevents the cell from overcoming the third checkpoint of the cell cycle, therefore it arrests in the prometaphase-anaphase transition (checkpoint).*

The second one would be:

*The carbamazepine prevents the polymerisation of the polar microtubules between the centrosomes. Therefore, even if the centrosome duplicates, the second one cannot migrate (migration) to the opposite pole during prophase and a monopolar spindle is generated, with the same consequences as the previous hypothesis.*

To check which is the right option, if the students ask the teacher to see the chromatin of the cell (Figure 1B), they will realise that there is already an attachment between the microtubules and the chromosomes. But, in the absence of a bipolar spindle, chromosomes are not congressed at the equatorial plate nor bi-orientated, so the cell must be arrested at prometaphase. Moreover, if they ask to see the labelled centrioles, forming the centrosomes (Figure 1C), they will confirm that their duplication has taken place, but not their migration, so the correct hypothesis would be the second one.

Thereby, learners should combine and contextualise the next eight ideas about the mitotic spindle model (coded in parentheses throughout the text): centrosome duplication (duplication); microtubules polymerisation from the centrosome (polymerisation); centrosomes migration (migration); microtubules-kinetochores attachment (attachment); prometaphase (prometaphase), as a possible stage in which the treated tumour cell is arrested; cell cycle stages (stages) in which the different events occur; metaphase checkpoint (checkpoint); and drug's action (drug). Other ideas related to the task, but not

included in the reference response, are encoded as non-essential ideas (non-essential). For instance, the difference between tumour and treated cells. Thus, some students consider that cancer cells do not progress and divide through a normal mitosis and attribute the cause of the monopolar spindle to the tumour and not to the treatment.

### ***Data Sources and Data Analysis***

Data collection includes a) audio recordings of the discussions within the ten small groups, which are transcribed, and b) groups' written reports. As the researchers seek to examine the application of students' cell division knowledge in a classroom setting, a case-study approach is suitable to address this type of learning processes, because it helps to understand the meaning behind the learners' actions (Kyburz-Graber 2004). In this work, ten groups from two different classes are studied, since by analysing multiple cases it is possible to obtain more solid information and conclusions than if only one is considered (Yin 2018). A discourse analysis (Gee 2011) is performed to identify how the ideas are handled in each group, and then further explores how each group evolves in their use of these notions over the course of the task.

To analyse the students' discussions, the researchers have fragmented the transcripts into episodes, as units of analysis. According to Gee (2011), an episode is each sequence of turns of speech that focuses on the same activity or action. In this study, an episode is a sequence of students' individual interventions in which the same idea or set of ideas about mitosis are addressed. There is an episode shift when the reasoning changes by discarding some ideas or focusing on new ones. The following excerpt from group G is an example of the analysis carried out. The beginning of each of the two episodes is highlighted in bold:

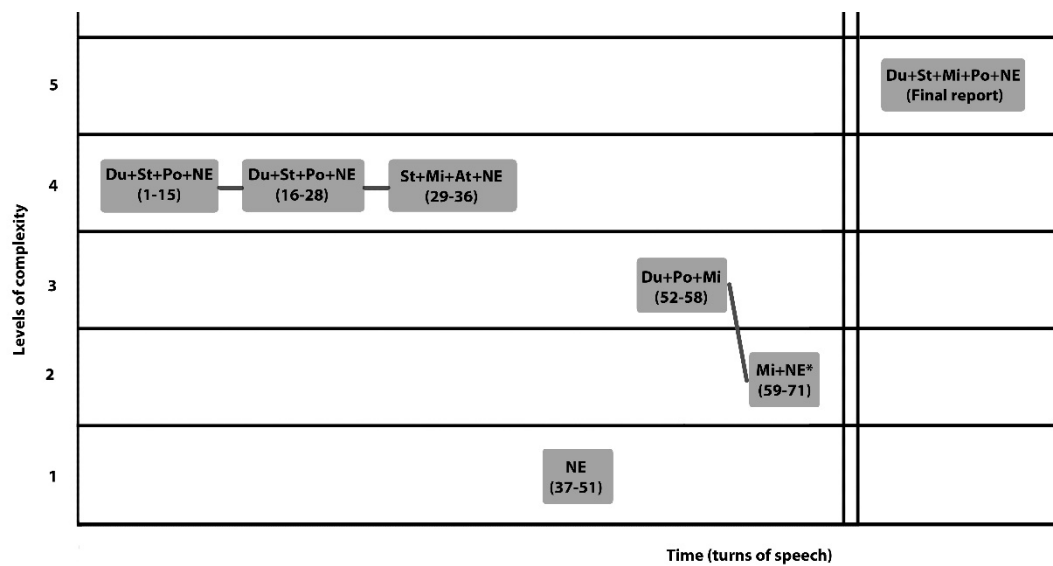
**61. Eve: *Okay, after seeing the photo (she reads while writing) we have seen that both (duplication) ...***

62. George: ...*centrioles* (he completes his partner's sentence) ...  
 63. Eve: ... *are in the same pole, because the treatment (drug) prevents their separation* (migration)  
**64. Ms. Nadia: *Have you written down the phase [in which the problem cell is] (stages)?***  
 65. Eve and George: *No, we have not*  
 66. Eve: ...*metaphase?*  
 67. George: ...*prophase, metaphase, or prometaphase* (prometaphase)?

In the first episode (turns 61-63), students are writing down their hypothesis, which fits the second option of the reference response. They combine three ideas: centrosomes' duplication and migration, and the drug's action. In turn 64, a new episode starts, because the teacher's question leads learners to integrate two notions in their dialogue, the stages of cell cycle and the prometaphase as a possible answer.

Then, after categorising the ideas used by the students throughout the speech, each episode is assigned one of the nine levels of complexity in the application of the mitosis model, depending on the number of notions that the small groups relate in them. Episodes in which students talk about non-task related topics have been ruled out. Besides, non-essential ideas handled within the same episode count as one. Therefore, the lowest level is 1, that includes episodes in which an idea is discussed; and the highest level is 9, as a result of combining the eight ideas of the reference answer with non-essential ones. For instance, the above episodes would be included within the levels of complexity 3 (turns 61-63) and 2 (turns 64-67), as students relate three and two notions in them, respectively. Finally, the small groups' progress in the use of the mitosis model throughout the activity is analysed in terms of students' discursive moves through different levels of complexity when reasoning about the problem (Bravo-Torija and Jiménez-Aleixandre 2017). To represent the discursive moves of each small group in their discussions, the researchers use discursive networks, adapting Kelly and Takao's (2002) scheme. These networks provide insight into the process of transforming learners' theoretical models into practical decisions to solve the task. In this study, they allow a deeper understanding of how

students move up and down the level of complexity in their use of the mitosis model over time (turns of speech), incorporating ideas they had not previously considered until they reach their final decision (Figure 2). In addition, asterisks are used to represent the teachers' scaffolding, reminding learners to build on the knowledge acquired throughout the activity and/or during the previous master sessions.



**Figure 2.** Discursive network of group B. Combined ideas are coded using the first two letters of each. The asterisks represent the teacher’s scaffolding.

As a brief example, it can be seen in Figure 2 that students combine four ideas from the beginning and during the middle of the speech, finally oscillating among five levels of complexity. Moreover, throughout the first three episodes the students already handle five out of the eight ideas needed to respond: centrosomes’ duplication and migration (Du, Mi); stages (St); microtubules’ polymerisation (Po) and microtubules-chromosomes’ attachment (At). It should be noted that in no case are these introduced by the teacher (i.e., without asterisk).

### RESULTS AND DISCUSSION

According to the first objective, Table 3 shows the ideas of the reference response integrated in the small groups' discourse. Two of them handle all the ideas in their

reasonings (I, J). Two others use all but one (G, H). One group mention six out of the eight ideas (F). Four groups use five (A, B, D, E) and the group C considers only half of the essential ideas. Besides, three of the groups handle ideas from the reference response expressly more than 20 times to solve the task. Specifically, in group J, students use key concepts about mitosis up to 40 occasions, combining them in different ways and repeating some of them several times throughout the speech.

**Table 3.** Contextualised ideas about mitosis used by each group during problem solving (grey shading). The number of times the groups handle each idea is written in italics.

<b>Idea/Group</b>	<b>A</b>	<b>B</b>	<b>C</b>	<b>D</b>	<b>E</b>	<b>F</b>	<b>G</b>	<b>H</b>	<b>I</b>	<b>J</b>	<b>Total</b>
<b>Drug</b>	<i>2</i>				<i>3</i>	<i>6</i>	<i>2</i>	<i>6</i>	<i>6</i>	<i>9</i>	<b>34</b>
<b>Duplication</b>	<i>6</i>	<i>3</i>	<i>4</i>	<i>7</i>	<i>3</i>	<i>6</i>	<i>4</i>	<i>5</i>	<i>5</i>	<i>6</i>	<b>49</b>
<b>Stages</b>		<i>3</i>		<i>3</i>		<i>7</i>	<i>4</i>	<i>1</i>	<i>7</i>	<i>2</i>	<b>27</b>
<b>Polymerisation</b>	<i>2</i>	<i>3</i>	<i>3</i>	<i>2</i>	<i>4</i>	<i>2</i>		<i>2</i>	<i>2</i>	<i>7</i>	<b>27</b>
<b>Attachment</b>	<i>1</i>	<i>1</i>	<i>2</i>	<i>3</i>	<i>2</i>	<i>2</i>	<i>1</i>	<i>1</i>	<i>7</i>	<i>5</i>	<b>25</b>
<b>Prometaphase</b>							<i>2</i>	<i>1</i>	<i>1</i>	<i>1</i>	<b>5</b>
<b>Checkpoint</b>						<i>1</i>	<i>1</i>		<i>1</i>	<i>3</i>	<b>6</b>
<b>Migration</b>	<i>2</i>	<i>3</i>	<i>3</i>	<i>3</i>	<i>3</i>		<i>2</i>	<i>1</i>	<i>2</i>	<i>7</i>	<b>26</b>
<b>Total</b>	<b>13</b>	<b>13</b>	<b>12</b>	<b>18</b>	<b>15</b>	<b>24</b>	<b>14</b>	<b>17</b>	<b>31</b>	<b>40</b>	<b>93</b>

The ideas of ‘centrosome duplication’ and ‘microtubules-chromosomes attachment’ are used by all groups in their discourses (Table 3). However, the ideas of ‘prometaphase’ and ‘checkpoint’ are considered by less than half of the groups. The most frequent idea among all groups is the ‘centrosome duplication’, but there are also 34 episodes in which students consider the ‘drug's action’. According to the authors, these findings show that learners are able to contextualise their mitosis conceptions within the problem. Less frequent notions are ‘checkpoint’ and ‘prometaphase’; so much so that the groups only allude to this stage five times, which is consistent with the findings reported by Orcos and Magreñán (2018). They point out that many textbooks omit the ‘prometaphase’ to simplify the content assimilation; despite its importance in understanding the cell division as a continuous process and not as fixed pictures

(Esquivel-Martín et al. 2021). Thus, in textbooks, events occurring during the prometaphase, such as the total disappearance of the nuclear envelope or the microtubules-kinetochores attachment, often appear divided between the prophase and metaphase, respectively. However, Esquivel-Martín et al. (2021) want to emphasize the dynamism of the process, presenting the metaphase as a virtual phase, which begins just as it ends. The ones that really exist are the prometaphase and the anaphase.

In terms of how each group combines and applies their ideas of mitosis to solve the task, there are three categories that represent more than 70% (66 out of 93) of the episodes (Table 4). Thus, the levels of complexity reached preferably by the students throughout the speech are those in which they combine two, three and four ideas, being infrequent that they relate more notions in the same reasoning. The number of episodes in the higher categories is much smaller. Thus, eight of them belong to categories 5-6, and only one episode is included within the seventh level of complexity, in which group J relates six out of eight ideas from the reference response.

**Table 4.** Summary of discursive episodes in the ten groups (A-J), considering the level of complexity (LC) achieved by combining ideas in each episode.

LC/ Groups	A	B	C	D	E	F	G	H	I	J	Total of episodes
Level 7, combining 7 ideas										1	1
Level 6, combining 6 ideas						1			1		2
Level 5, combining 5 ideas	1			1					3	1	6
Level 4, combining 4 ideas	1	3	2	2	2	2	2	2		4	20
Level 3, combining 3 ideas	1	1	1	2	1	4	2	4	4	4	24
Level 2, combining 2 ideas	2	1	2	2	4	3	2	1	1	4	22
Level 1, considering 1 idea	2	1	3	2		4		1	2	3	18
Total of episodes	7	6	8	9	7	14	6	8	11	17	93

None of the groups reaches the highest levels of complexity in their discourse, that is, they do not integrate eight or nine ideas when arguing. Firstly, this may be due to the fact that formulating complex hypothesis requires a great capacity for abstraction and extensive prior knowledge of the subject to which the theory refers (Verhoeff et al. 2018).

In this case, starting from a micrograph of the microtubules of a cell, students should infer what has happened during the whole process of cell division and when, which implies handling a fairly complete theoretical model that many students have not yet acquired.

Second, when interpreting the problem, most students resort to explaining what has happened to the subcellular structures at a structural-functional level (presence/absence of structures and their most direct consequence, e.g., *'as a centrosome is missing, the whole spindle is not formed'*), without considering which cell cycle stages are affected, or what mechanisms the cell has to prevent the cycle from continuing when something is wrong. This is in line with the students' principle of parsimony in problem solving: *when constructing a theory, one should not make more assumptions than the minimum needed*; also known as Ockham's razor (Koichu 2008). Thus, learners tend to handle the simplest notions and to relate as little information as possible, i.e., they try not to "step out of their comfort zone", which is based on their previous training and experience (Hulse 2006).

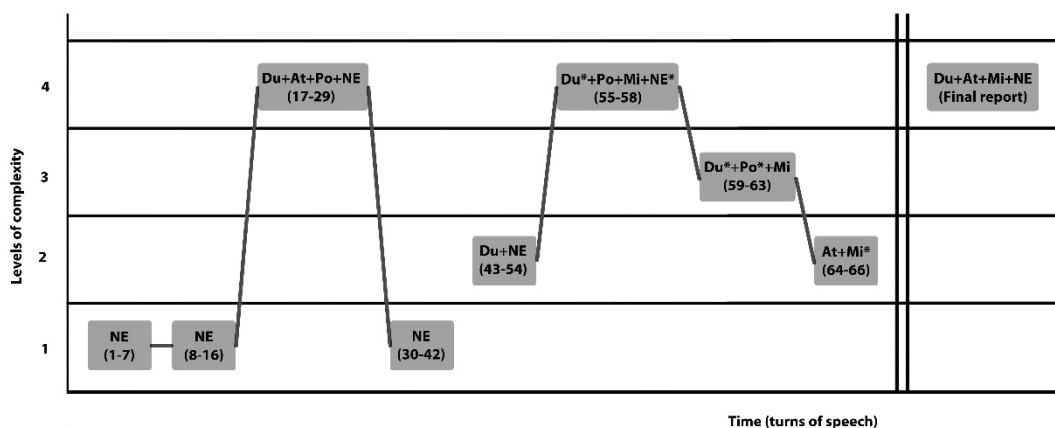
On its part, regarding the groups' written reports, three reach high levels of complexity: 6 (J), 7 (F) and 8 (I). Four of them are included in the fifth level of complexity (B, C, G, H) and two in the fourth (D, E). Only group A uses a single idea (specifically, that of 'duplication'), probably due to lack of time, even though students verbally handle other relevant concepts throughout their discussion. Thereby, this group co-construction of meanings approach helps students deepen their understanding and extend their knowledge about mitosis in novel contexts, reasoning about different elements and events of the process, which they would certainly not otherwise consider and/or relate to.

Concerning the second research question: *how is the students' progression in the use of the mitosis model throughout the activity?* the groups' discursive networks have facilitated the groups' comparison as the students elaborate their decisions about what

has happened to the problem cell. Thus, two discussion groups (C and J) with different performance have been selected as examples.

Group C is dominated by lower levels of complexity, combining 1-2 ideas per episode, many of them non-essential. A maximum of three ideas considered in the reference response are integrated at the same time, even in the final report where all the reasoning is synthesised. Group J is the only one that manages to combine seven ideas (six of them belong to the reference response) in the same episode, without any of them being introduced by the teacher. In addition, the overall performance of this group is good, as the level of complexity of most episodes is three or more.

***Group C: Predominance of lower levels of complexity***



**Figure 3.** Discursive network of group C. Combined ideas are coded using the first two letters of each (see method). The asterisks represent the scaffolding of the teacher.

The oral discourse from group C (Figure 3) is continuous and ranges only among four levels of complexity, moving between the use of non-essential ideas and the final combination of two (attachment and migration\*). Among the non-essential ideas (turns 1-16), a recurrent practice in this and in most of the groups is to consider the metaphasic spindle model, frequently shown in textbooks, as a reference. According to the authors, students are comparing it with the problem's micrograph when they claim that '*the other part of the spindle is missing*'. Furthermore, the group introduces another non-essential idea (turns 8-16) when a student argues: '*the cell is like this* (looking at the picture)



*because the chromosomes have come out*'. This reflects a lack of knowledge of the cellular interior, as if the structures could 'leave the cell'. Thus, students sometimes attribute functions of the organism to the cell (cellular anthropocentrism), according to Mengascini (2006); and this can be extrapolated to its subcellular structures.

It is worth noting the leadership of Nico throughout the speech, who integrates most of the conceptions. Thus, in turns 17-29, he begins to combine ideas from the mitosis model, reaching the fourth level of complexity. On the one hand, he develops the first hypothesis, that corresponds to the first option of the reference answer, relating the notions of 'duplication', 'polymerisation' and 'attachment' (see the excerpt). On the other hand, he clarifies to his colleagues one of the non-essential ideas they handle (turn 23), pointing out that even if some structures do not appear stained or labelled, they are still there (turns 25 and 27). Hence, besides promoting that students relate ideas, this activity contributes to improve their abstraction and spatial vision skills, since by seeing only one structure (microtubules) they have to infer where and how the rest are (Esquivel-Martín et al. 2021):

20. Nico: *It [the cell] lacks a centriole (duplication), so the mitotic spindle is not formed from it (polymerisation) and cannot connect to the chromosome to pull it(attachment). Therefore, it cannot be divided (...)*

23. Noah: *The cell is also missing chromosomes; I do not see them there (non-essential)*

24. Raoul: *That is what I have said*

25. Nico: *But... you can only see the mitotic spindle there*

26. Noah: *And the nucleus?*

27. Nico: *You can only see the mitotic spindle there, this green thing (pointing to the micrograph), you could not see it [genetic material] there either (that is, in other microtubules' micrographs of the activity, see phase 7 of Table 2)*

When Ms. Irina invites them to explain another option (turns 30-42), the complexity drops again to the lowest level, as Noah regains the non-essential idea that *'a part of the mitotic spindle is missing'*. So, the teacher asks: *'how could you determine if any of your hypotheses are correct?'*, to which Noah answers: *'checking that only half of the mitotic*

*spindle is present*'. Ms. Irina deeps on the student's reasoning: *'Are you telling me that we have taken a photo and cut it in half?'* As Noah answers in the affirmative, the teacher reveals that this is not what has happened.

Then, Nico reaches the second level of complexity by breaking the continuity of the discourse (turns 43-54), as he returns to his hypothesis of non-duplication of the centrioles. Ms. Irina adds: *'Ok, let us assume one centriole is missing, but... how can we see if it is actually missing?'*, initiating a procedural debate on structure marking (non-essential idea), which ends with Nico asking to see the orange-labelled centrioles.

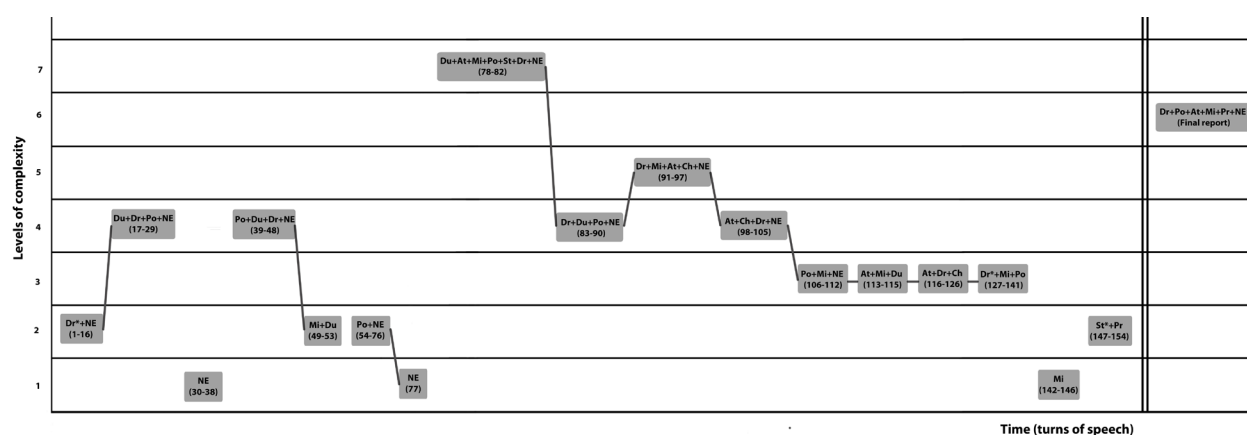
The discourse moves to the fourth level of complexity (turns 55-58) when Ms. Irina reviews the options, reintroducing two ideas into the discussion: duplication\* and non-essential: metaphasic spindle\*. Then, she asks the students to infer how the problem's micrograph would look if Nico's hypothesis were correct, to which he answers (turn 58): *'There would only be an orange dot [centrosome] on one side, that is why the other part [of the spindle] is not there (migration), because it cannot grow between them (polymerisation)'*. After (turns 59-63), the teacher repeats Nico's reasoning using the ideas of duplication\* and polymerisation\* and shows the learners the figure 1C. Nico confirms his idea and concludes: *'the centrioles have not migrated to opposite poles (migration), so it [the spindle] has not grown between them (polymerisation)'*. Taking advantage of this, at the end of the session (turns 64-66), Ms. Irina tries to get the students to further explore the implications for the cell if centrosomes do not migrate (migration\*), such as the impossibility of chromosomal congression and subsequent arrest at prometaphase. She fails, because as mentioned above, students stay in the 'comfort zone' (Hulse 2006). They only consider how the lack of a centrosome affects the microtubules-chromosomes' attachment:

64. Ms. Irina: *And... if each one [centrosome] does not move to one side, what happens?*

65. Raoul: *That they* [microtubules] *cannot attach to the chromosome on both sides and pull* (attachment), *so they just pull on this side*
66. As Ms. Irina nods, Iris says: *What a clever!*

Then, according to this group, if chromosomes/chromatids separate into two different poles, mitosis continues; if they all go to one side, the process cannot end. Therefore, learners are able to attribute causes to effects in a known theoretical context, relating the function of structures (Bravo-Torija and Jiménez-Aleixandre 2017). This also shows that they assign the main role to the genetic material in mitosis (Dikmenli, 2010).

### ***Group J: Great performance and highest complexity in their oral discourse***



**Figure 4.** Discursive network of group J. Combined ideas are coded using the first two letters of each (see method). The asterisks represent the teacher's scaffolding.

The oral discourse of group J (Figure 4) has the most episodes (17) and is the most discontinuous. Students combine the same number of ideas at the beginning as at the end (2) but oscillating between a greater number of levels of complexity throughout the discussion (6). Students start (turns 1-16) by combining two ideas, the fact that the cell has been treated (drug\*) and the idea that '*half of the spindle is missing*' (non-essential: metaphasic spindle), after Ms. Nadia makes it clear to them that they are seeing a whole cell and not a part (other non-essential idea). This leads Gunter to affirm: '*this is because a centriole is missing* (duplication)', introducing the first idea of the mitosis model that fits the first hypothesis of the reference response. With his intervention, the speech moves to the fourth level of complexity (turns 17-29), since this notion is joined by the two

previous (half a spindle is missing because the cell is treated). In addition, Alex complements the argument by introducing the idea of microtubules' polymerisation from the centrosome, since he relates the lack of microtubules with the lack of the centriole.

However, the discourse descends to the lowest level of complexity, when Gunter asks: '*but... is the chromatin there or not* (referring to the figure 1A)?' which triggers a discussion for a few turns (30-38) on laboratory methodological procedures (isolated episode: non-essential idea). In turns 49-53, the speech returns to the fourth level, since the students combine the same ideas as in the second one, while telling them to the teacher. This leads Ms. Nadia to show them the centrioles micrograph, which makes Gunter combine the idea of 'duplication' with the 'centrosomes migration': '*Oh, boy! There are two of them, but they are on the same side*'. In the next episode (turns 54-76), the continuity is lost again, since the teacher invites them to consider the difference between the centriole and the centrosome (non-essential), something they doubt:

64. Alex: *but what is a centrosome?* (...)

66. Alba: *I just don't know* (...)

69. Gunter: *these are centrosomes I think* (he refers to the figure 1C) (...), *I mean, the centrioles with the microtubules* (polymerisation)

This is a terminological discussion quite widespread among the groups, sometimes promoted by the teacher, as in this case. On the one hand, some students do not distinguish the centrosome from the centrioles, which may be due to the fact that they are two concepts with a similar spelling. This difficulty in cell division learning has also been noted by Rohrer (2012). According to this author, in most middle school science texts, the questions in each task focus on the same concept, preventing students from having to differentiate between similar ones. Hence, activities such as the one analysed here, promote the scientific language acquisition, since students should make use of it by speaking and writing science (Jiménez-Aleixandre and Reigosa 2006).

On the other hand, among those who do distinguish centriole and centrosome, there is another difficulty, that of interpreting microscopic images, a scientific practice unfamiliar to learners (Fernández and Jiménez-Tejada 2018). Thus, by identifying the structures in the figure 1C, some learners understand that each ‘orange dot’ corresponds to a centriole rather than to the whole centrosome, which affects the final reasoning on centrosome duplication. Each dot corresponds to the gamma-tubulin structure that forms the centrioles. However, in animal cells, each centrosome has two very close centrioles (non-existent in plant cells), which are cylindrical structures arranged perpendicularly, indistinguishable under the optical microscope, with the pericentriolar material around them. Therefore, in this case, two close dots are seen because the two centrosomes have not separated during prophase. Even in the next episode (complexity level 1), students assess the possibility that *‘the centrosome is the agent causing the stop in cell division’*, relating it to the tumour condition of the cell (non-essential). Nevertheless, in turn 78, the discourse moves to the maximum level of complexity among all the groups (7), as they mix a valid hypothesis (turn 78) with another one that confuses the mechanism of action of the drug (turn 82), as if it accelerates the rate of microtubules’ formation:

78. Alex: *if the two centrosomes are on one side of the cell (migration), the spindle is only able to pull on that side (attachment) so the cell cannot be divided, write that down! It is a good idea (...)*

82. Gunter: *there is a centriole... the centrioles are divided (duplication) at the interphase (stage) to prepare the mitosis, taking out the microtubules (polymerisation) to form the whole spindle and all that; the drug (drug) has accelerated the formation of microtubules at the beginning, then they have stuck together (non-essential), which makes it impossible for the cell to divide.*

From that moment on, students combine between three and five ideas in the following episodes, except the two finals. In turn 98, Ms. Nadia asks them about the second hypothesis. To explain why microtubules do stick together (non-essential), Gunter responds handling indirectly the notion of metaphase ‘checkpoint’, understood as the need for chromosomal congression and biorientation for the progression of cell division,

and ‘attachment’: ‘(...) *instead of the chromosomes congress (checkpoint), no genetic material is congressed, which causes the microtubules to pull together and stick together... which is a horrible idea*’. As his classmates do not understand him, he clarifies: *I think this [the monopolar spindle] was formed because of the forces... because when they [the microtubules] pull [the chromosomes], they make a force to divide (attachment) and they come together because of the drug (drug)*’.

When writing the options (turns 106-112), surprisingly, Gunter points out that the first is: *‘the cell takes out microtubules forming centrosomes (polymerisation) and they remain so close (non-essential) that there are not two different poles (migration)’*. This shows an alternative idea about centrosome formation from microtubules and not the other way around (reverse polymerisation), which confirms students’ lack of knowledge about this structure (Esquivel-Martín et al. 2019). From here, they keep combining three ideas until the penultimate episode, in which they only use one. It should be noted that in turn 113, learners again handle one of the reference response’s ideas in the opposite direction (reverse migration), since they consider that, *‘because the forces are reversed, instead of the microtubules pulling out [the chromosomes] to divide in two (attachment)... they come together until the two centrosomes (duplication) are joined (migration)’*.

Furthermore, in turns 116-126, Gunter uses again the notion of ‘checkpoint’, pointing out that *‘due to the treatment (drug), the microtubules pull towards the same pole (attachment) and there is no time for the chromosome congression’*. Students end up handling fewer ideas in the final two isolated episodes because they are reviewing their writing. In turns 142-146, they try to find the word to define the movement of one centrosome to the opposite side (‘migration’), but they do not remember it. Finally, in turns 147-154, Ms. Nadia reminds them to think about the stage the cell is in (stages\*), being one of the few groups considering that the cell could be at ‘prometaphase’.

By comparing the discursive structure in the two groups selected as examples (8 and 17 episodes), a clear common pattern has not been found, as the decision-making process, connecting the theoretical models with other data provided, is far from linear and, sometimes, not continuous either. Thus, some of the intermediate oral episodes exhibit higher levels of performance than the final report (e.g., group J). Therefore, analysing the students' discursive moves in depth allows to fully understand the decisions made throughout the activity. If only written statements are evaluated, this valuable information is lost (Bravo-Torija and Jiménez-Aleixandre 2017).

The level of complexity increases especially from the middle, as learners add new ideas to the discussion and combine them in different ways. However, students tend to combine more ideas in their written productions than in the last episodes of their speeches, possibly due to the effort of synthesis they make when writing the reasoning followed. In both groups, teachers exert influence, either by incorporating ideas directly or by reorienting the discourse. This leads to certain conceptions predominating in a particular class. For example, the drug's action is mentioned much more often in Ms. Nadia's (Table 3), as the teacher emphasises at the beginning of the session the difference between treated and untreated tumour cells. Teachers also remind some groups to point out the stage of the problem-cell, otherwise they would probably not indicate it.

Throughout the speech, the teacher-learners and learner-learner's interactions complete and increase the coherence of the students' ideas, usually helping them to distinguish which ones are valid (Kali, Linn, and Roseman 2008). Additional evidence requested by students to test their hypotheses are also useful in solving the problem, as indicated in the literature (Evagorou and Osborne 2013). Nevertheless, not all of them need extra-information to formulate options included in the reference response. Furthermore, the researchers consider that the activity design promotes the emergence

and verbalization of alternative ideas on which teachers can intervene directly. Therefore, these kinds of dynamics contribute to knowledge meaning-making when talking about science (Esquivel-Martín et al. 2021).

## **CONCLUSIONS AND EDUCATIONAL IMPLICATIONS**

This study provides literature with a practical example of how to analyse students' application of their mitosis models to solve a realistic problem, in terms of discursive moves. First, the designed activity encourages Biology learners to develop and apply a set of notions about cell division to justify why the treated tumour cell cannot conclude its mitosis, such as the need of 'centrosomes duplication', 'microtubules-chromosomes attachment' or 'microtubules polymerization from the centrosomes' for the process to be complete. These conceptions are handled by all groups several times. Moreover, some of them also consider understudied ideas that move away from the traditional account of the process, such as the 'prometaphase' (Orcos and Magreñán 2018).

Second, the activity also promotes that students stop focusing on the metaphase to solve the problem, since the most important events for the successful completion of mitosis take place earlier. Likewise, learners do not need to visualize the state of the chromosomes but should focus on the formation of the mitotic spindle, considering the implications of possible anomalies in the process such as the monopolar spindle organisation. This contributes to improve the students' knowledge about this structure, to which less time is devoted in the teaching of mitosis (Esquivel-Martín et al. 2019).

Third, in addition to examining if the meanings that students attribute to the mitosis related terms as 'centrosome' or 'prometaphase' are appropriate, the researchers focus on how learners evolve by combining their ideas to solve the task. Thus, the activity encourages learners to establish relationships among mitosis contents, instead of handling them in an isolated way (Rohrer 2012). The categorisation of this study allows to



distinguish between different levels of complexity in the process of contextualization of cell division, which is the way students connect what they know to the task. Thanks to the discursive networks, it can be noted that the decision-making process is far from linear. Some groups almost reach the highest levels of complexity at certain moments of the discourse. Nevertheless, although all of them can solve the problem by formulating at least one valid option, students show difficulties in integrating knowledge, and the combination of a reduced number of mitosis-related ideas predominates when arguing.

This reinforces the need to give learners the opportunity to solve realistic health-related problems before finishing their compulsory schooling (Esquivel-Martín et al. 2021). Therefore, more attention should be paid to the design of activities, encouraging the students' participation and cooperative application of knowledge. Such learning environments could improve students' scientific literacy while simultaneously fostering their interest and engagement in science, since there is a high drop-out rate between natural science and technology careers.

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