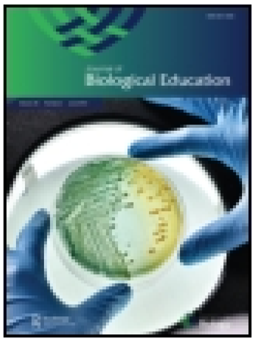

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Research paper

An action-research programme with secondary education teachers on teaching and learning photosynthesis

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We describe part of an action-research programme in Spain which was based on metacognitive reflection. The participants were four science teachers in a secondary school during the 2004–05 and 2005–06 academic years. During the study, they each analysed their own pupils' alternative ideas on photosynthesis and their teaching methods as recorded in videos of their classes, and followed this by planning new teaching units. The present communication focuses on the case of one experienced teacher. The results showed that the teacher's reflection on his pupils' commonest alternative ideas and his own classroom teaching led him to plan new teaching units for the second year of the study which took those alternative ideas into account, and included new strategies, resources and activities. The programme has contributed to the teacher's professional development, impacting significantly on the elements that form part of his teaching, and positively affecting the learning and conceptual change of his pupils.

Keywords: professional development; action-research; secondary teachers; teaching and learning photosynthesis

Introduction

The teacher is the key to the qualitative improvement of education systems, and determines the success or failure of whatever curricular reform or innovation is to be implemented. Understanding the processes of science teachers' professional development has become one of the principal themes in the agenda of science education research (Hewson 2007), and is an essential element in the planning and practice of teacher education programmes.

Our work forms part of a programme of professional development of secondary education science teachers conducted by various teams of teacher-researchers in secondary schools in Spain, Portugal and Argentina on different topics of the sciences (Bañas et al. 2009; Domingos-Grilo et al. 2009; Peme-Aranega et al. 2010; Vázquez et al. 2010).

Ricardo is a secondary education biology teacher who participates in an action-research group in his school. We examine how his classroom practice in teaching photosynthesis and his pupils' ideas about the concept evolved over two years.

Professional development of experienced science teachers

Science teaching research has been dominated since the 1980s by the constructivist paradigm, which has led to considerable progress in many aspects of the teaching and learning of science. Constructivist-based programmes for the professional development of teachers have evolved from initial conceptual change by substitution through competition towards more gradual change. These programmes progressively incorporated such new concepts as conceptual ecology and the changing status of ideas, and introduced perspectives shared with other orientations such as action research or metacognition (Hewson et al. 1999; Mellado et al. 2006).

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Experienced science teachers have beliefs and teaching models which are very stable and resistant to change, having been formed and consolidated over the course of their education and careers (Jeanpierre et al. 2005). In some cases, this resistance is because they are satisfied with educational models that have been consolidated by professional experience. In other cases, it is because there exist obstacles in the education system and the teaching community itself that reinforce traditional models (Peme-Aranega et al. 2010; Vázquez et al. 2010).

Research with science teachers has found that experienced teachers do not usually make drastic changes. Instead, they progressively put the ideas that seem to them to be important and at the same time attainable into practice (Freitas et al. 2004). For experienced teachers, ongoing education cannot be designed and presented as a change, but rather as an internal process of growth and gradual development based on what they already think and do, on the real problems of science teaching and learning, on their everyday concerns, and on the context in which they work. The professional development of science teachers will not take place by going from one set of models to another, but by reaching a greater complexity both in their reflection and in how they teach (Vázquez et al. 2010).

Teachers' professional development is stimulated by successive processes of metacognitive self-regulation, based on their reflection, comprehension and monitoring of what they think, feel and do, and of the changes that they put into effect (Bañas et al. 2009). This involves awareness of what problems of teaching and learning might be improvable, elaborating new activities, materials, and teaching proposals, putting them into practice in the appropriate context, successive reflection on their teaching and on the results in their pupils' learning, and comparing their practices with other cases to again revise and self-regulate them (Marx et al. 1998).

Professional development has to go together with personal and social development (Bell and Gilbert 1994). It will be difficult to put changes into effect unless they are compensated affectively and contribute to greater personal job satisfaction. Teacher education programmes must also treat the teacher as an integral member of a group, providing collective development experiences and encouraging collaboration. In summary, they must consider the school as being the most suitable place for professional development and as the unit for change.

Action research in collaboration with other teachers into situations and problems in science teaching and learning which are important and of interest for their own classes – in particular longitudinal studies of their own case – is an extraordinarily effective strategy for professional development in the medium and long term. These investigations are done 'by' and 'with' teachers, in teams that cross disciplines and levels, where the teachers are not consumers of external knowledge, but co-producers and agents of change in the problems that really concern them in their classes (Ritchie 2008).

The teaching and learning of photosynthesis

For science teachers, the axis of their professional development has to be science education, as the content to be taught conditions both their role in the class and the teaching strategies they use (Abell 2007). The Pedagogical Content Knowledge construct of Shulman (1986) – knowledge that is specific to how each particular subject is taught, and a form of reasoning and educational action by means of which teachers transform the subject matter into representations that are comprehensible to the pupils – has been the impulse behind many studies of science teachers, because change in the teachers is developed on particular content (*eg* in the case studied here, on photosynthesis: Abd-El-Khalick 2006; Kapyla et al. 2009; Park et al. 2011), not on the abstract.

Science education studies have investigated extensively pupils' spontaneous ideas concerning scientific concepts. These ideas are deeply rooted, and often do not coincide with scientific theories. For instance, secondary education pupils have alternative ideas on photosynthesis, many of which persist after they have left school (Cañal 1999; Charrier et al. 2006; Haslen and Treagust 1987; Sacit Köse 2008).

Science teachers can themselves have alternative ideas about scientific concepts, at times coinciding with those of the pupils (Brown and Schwartz 2009), thereby demonstrating how persistent these ideas can be. Previous research has shown that a fundamental factor that stimulates science teachers' reflection and change is when they become aware of the existence of the pupils' alternative ideas (da Silva et al. 2007).

Research questions

The following research questions were addressed in the present study:

(a) How does Ricardo's classroom practice evolve during the two years of investigation after participating in the action-research programme?
(b) At the compulsory secondary education level, what are the pupils' alternative ideas about different aspects of photosynthesis?
(c) How do those ideas evolve as a result of the teachers' action-research programme? Is the pupils' conceptual evolution permanent or only temporary?

Methods

In a broader study, we carried out an action-research programme with three science teachers in a secondary school during 2004–05 and 2005–06. One of the aspects analysed was the influence of the professional development of teaching staff on the evolution of their pupils' ideas. Each school year included two cycles of action-research (planning, action, observation and reflection).

That study was aimed at describing and analysing not only what those teachers thought and did, but also the results of their action, and at fostering a true professional education of self-regulation of the teaching–learning process for the participants.

In the present article, we shall focus on the case of a teacher named Ricardo. The study was conducted with pupils of the 10th year (ages 15–16) of compulsory education in a secondary school in Elvas (Portugal). Ricardo was a biology education graduate with 14 years' teaching experience. Simultaneously with his work as a secondary education teacher, he completed a doctorate in cell biology.

The data collection procedures were as follows:

(a) A questionnaire designed to determine the conceptual evolution of the pupils' ideas on photosynthesis (see Annex). This questionnaire was given to the pupils before, immediately after, and eight months after they had studied photosynthesis.
(b) An initial interview with the teachers to obtain overall information on the teacher's profile and actions.
(c) Class videorecordings to determine the evolution of the teachers' classroom practice. Three of Ricardo's classes were videotaped in the first year, and four in the second, during his teaching of the topic of photosynthesis.

With respect to the analysis of teachers in science education research, there have been numerous proposals of models of teaching. In our study, we simplified these models, reducing them to two basic orientations: technical/transmissive and inquiry/constructivist, the first teacher- and content-centred, and the second pupil- and learning-centred. These two orientations were crossed with a system of six categories: planning, teaching methods, activities, classroom climate, resources and evaluation.

In the teacher's classroom practice, we also analysed during the two years the actions which reinforced (R) or generated (G) alternative ideas in the pupils or, on the contrary, fostered their conceptual change (F). In the analysis, each information unit is coded and inserted into Table 1 from which the data are extracted for the qualitative content analysis and the quantitative analysis of the frequency of the actions.

An essential element for the development of metacognitive strategies was the collaborative work carried out by the four teachers of the school. During the study, the participating teachers analysed their pupils' alternative ideas on photosynthesis, and the teaching methods they themselves used from observation of the videorecordings of their classes. We would highlight the extraordinary richness of this group of teachers' work sessions. In these, among other topics, they discussed their pupils' alternative ideas about photosynthesis, their teaching methods using videorecordings of classes as a basis, and planned new teaching units to put into practice in their classes in the second year.

It was agreed from the beginning that the teaching unit would be constructed according to a constructivist perspective, with the pupils being active elements, constructors of meaning and of their own knowledge. The teacher's role would be one of 'guide', 'facilitator', or 'mentor' in the pupils' construction of knowledge, selecting and organising learning situations that would foster the pupils' conceptual development. Crucial in planning this unit were the data obtained from the questionnaires given to the pupils during the first year. These showed what the pupils' alternative ideas were, so that they could be used as the basis for the development of the teaching and learning process.

Practical activities were assigned a key role in the new teaching unit. They were oriented as attempts to solve problems instead of as illustrations of the teacher's explanations. The pupils were to take part in setting up the experiments, collecting data and interpreting it in the light of the information available, and drawing reasoned conclusions. Activities of synthesis were also promoted, the aim being to relate knowledge from different areas and to stimulate cognitive conflict with the pupils' pre-existing ideas in order to facilitate their conceptual restructuring.

Results

In the initial interview, 56% of Ricardo's statements corresponded to a conventional/technical, teacher-centred orientation, with only 9% corresponding to an inquiry/constructivist, pupil-centred orientation, and the remaining 35% to an intermediate model.

The interview data indicated that Ricardo was initially greatly concerned to comply fully with the programme, seeing this as immersed in a teaching situation imposed from above and, as such, unalterable. He saw his principal function to be one of explaining the topics and making them understandable for his pupils. To this end, he would use resources that were illustrative or demonstrative when necessary. He saw himself as a specialist who was thoroughly familiar with the topics, and whose function was to transmit these topics to the pupils. The

Table 1. Model used to insert the information units for the qualitative and quantitative analyses

ACTIONS	Conventional/ technical		Inquiry/ constructivist		Reinforced/ generated		Fostered	
CATEGORIES	First Year	Second Year	First Year	Second Year	First Year	Second Year	First Year	Second Year
Planning								
Methodology								
Activities								
Class environment								
Resources								
Evaluation								

pupils' function was to listen, capture, and memorise the information, and to do exercises to demonstrate that they knew what the teacher had explained. The textbook was the main support. Ricardo regarded evaluation as something to be done at the end of the unit in order to classify the pupils. It did not occur to him to look for alternative ideas of his pupils that might represent barriers to their learning.

With respect to classroom observations, Figure 1 shows the quantitative results of Ricardo's classroom teaching practice in photosynthesis in the six categories established for the two basic orientations – technical/transmissive and inquiry/constructivist – during the two years of the study. The first year was dominated by a conventional/technical orientation centred on the teacher's explanations. This was especially so in the methodology, activities and class environment categories. The resources used in the first year were varied, unlike the declarations of the initial interview, which reflected a focus on the textbook. During the second year, however, there was a notable predominance of the inquiry/constructivist orientation, much more pupil-centred.

Another aspect of the classroom practice that was analysed was the frequency of Ricardo's actions that generated (G) or reinforced (R) the pupils' alternative ideas, or, on the contrary, fostered (F) their conceptual evolution. Figure 2 shows the evolution of these actions between the two study years, according to the six categories established.

During the first year, the largest group of actions were those which generated or reinforced the pupils' alternative ideas in the planning, methodology, evaluation and activities categories. During the second year, this group of actions decreased substantially, and was replaced by actions that facilitated the pupils' conceptual development in all the categories analysed.

The following is the transcript of an example of interactive action that facilitates (F) the pupils' conceptual evolution:

[Ricardo. Year 2. Classroom 1]

[Pupil 5: Autotrophs.

Ricardo: Who put autotroph?

(Most pupils raise their hands)] [2.6, I+, F]

[Ricardo: Why?

P10: They are able to produce organic matter.] [1.7, I+, F]

[R: Who said heterotroph?

P13: . . . why?

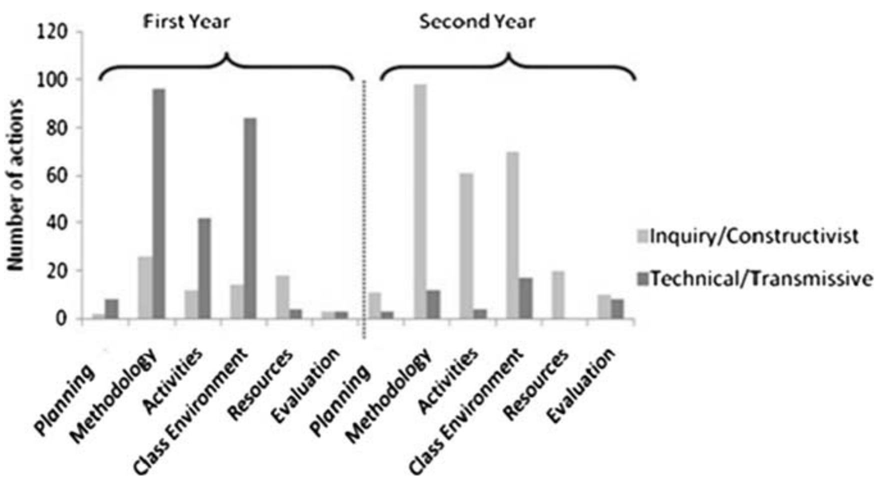

Figure 1. Evolution of Ricardo's teaching models in classroom practice

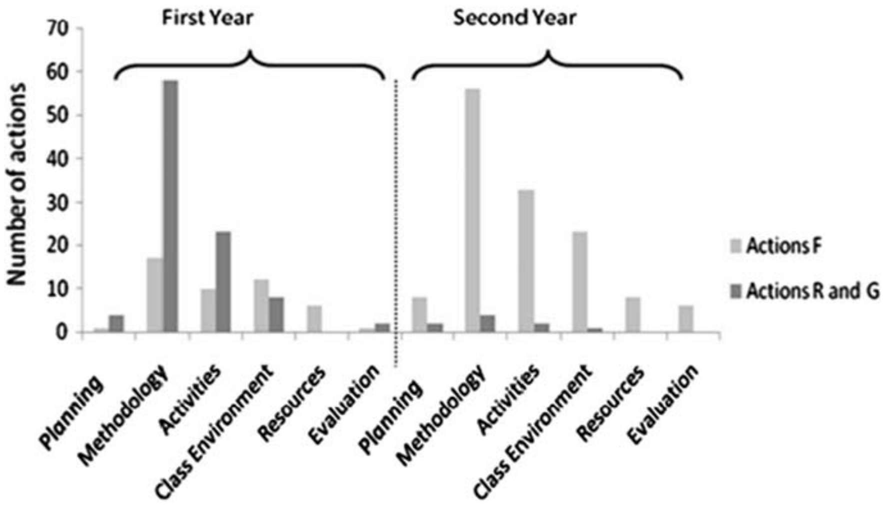

Figure 2. Evolution of Ricardo's actions in classroom practice that generated (G) or reinforced (R) the pupils' alternative ideas or on the contrary fostered (F) their conceptual evolution

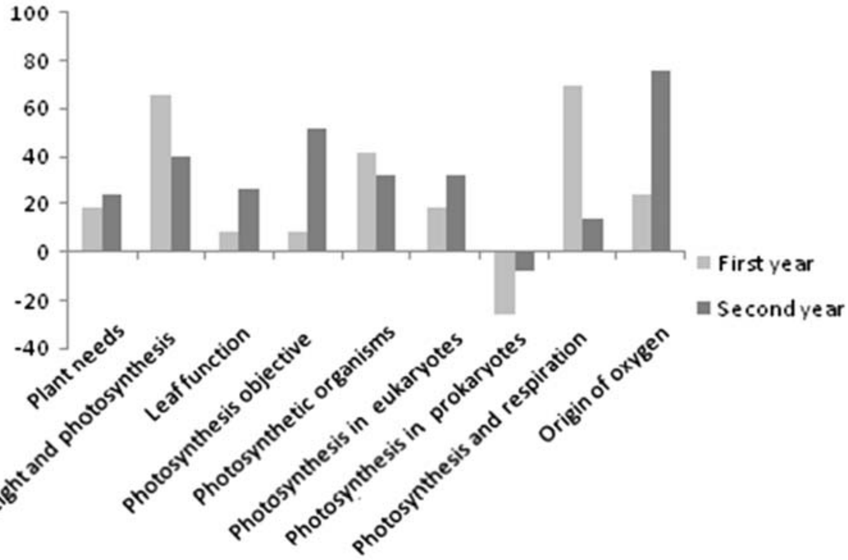

Figure 3. Percentage variation of Ricardo's pupils' ideas about photosynthesis before and immediately after teaching the topic of photosynthesis in the two years of the study

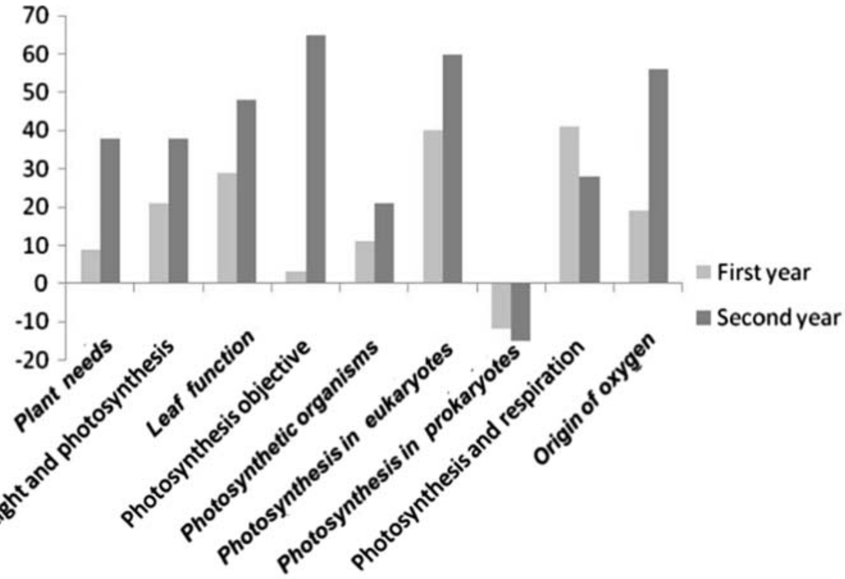

Figure 4. Percentage variation of Ricardo's pupils' ideas about photosynthesis before and eight months after teaching the topic of photosynthesis in the two years of the study

P13: They are heterotrophic because . . .

R: Let's see. For a heterotrophic organism, what is necessary?

P5: That there is organic material for it to feed on.

R: And on the primitive Earth, there already was organic material?

P9: No. They had to produce it.] [6.1, I+]

[R: Was there no organic matter? In the previous question you all told me that there did exist organic matter, and you even explained how it was formed. Were autotrophs necessary to form the first organic matter?] [2.2, I+, F]

[P8: No, it is formed abiotically.

R: So, the first living things may or may not have been heterotrophic?

P9: They could.] [4.12, I+, F]

[R: Could? Why?

P5: Because there existed organic molecules synthesised abiotically in the atmosphere.

Ricardo: Exactly.[[3.13, I+, F]

The next example shows how Ricardo generated (G) and reinforced (R) the alternative idea that photosynthesis is the inverse process of respiration, but also clarifies the confusion between pulmonary ventilation and cell respiration:

[Ricardo. Year 1. Classroom 1]

[Ricardo: What do they need to respire for? Don't confuse respiration with pulmonary ventilation. We are referring to cell respiration. What is cell respiration for? The respiration that occurs inside cells?] [2.6, I-, RG]

[P6: To produce glucose.] [4.12, I-]

[R: No, respiration is the reverse. In the equation of photosynthesis, if I put this arrow the other way round, I get the equation for cell respiration.

P6: It is providing oxygen to the cell.] [2.16, I-, RG]

[Ricardo: No. In cell respiration oxygen is used up. If I put the arrow the other way, I get the equation for cell respiration, so oxygen is used up and carbon dioxide and water are produced.] [2.9, I-, RG]

In the following, we show how the pupils' ideas on photosynthesis evolved during the two years. As these are different groups of pupils, we shall not present the absolute results for each year, but the evolution of the results of applying the questionnaire before and immediately after teaching the topic of photosynthesis in each year (Figure 3), and before and eight months after teaching the topic of photosynthesis in each year (Figure 4). These data allow us to compare this evolution in the first year during which the teacher used a mainly technical/transmissive methodological approach with that in the second year in which the methods were based mainly on inquiry/constructivist principles.

Figure 3 shows the evolution of the pupils' ideas about photosynthesis, comparing the results of the tests given before and immediately after teaching the topic for both the first and the second years.

There was an improvement in the second year compared to the first, immediately after teaching the topic, in the concepts of the requirements of plants, photosynthetic organs in plants, purpose of photosynthesis, photosynthesis in eukaryotes, and the origin of the oxygen released during the photosynthesis. However, the pupils got better results immediately after the topic had been taught in the first year in concepts related to light and photosynthesis, photosynthetic organisms, and photosynthesis and respiration in plants. The worst result in both years corresponded to the concepts related to photosynthesis in prokaryotes. In these concepts, the pupils regressed relative to the ideas with which they began the course.

Figure 4 shows the evolution of the pupils' ideas about photosynthesis, now comparing the results of the tests given before and eight months after teaching the topic for both the first and the second years.

There was an improvement in the second year compared to the first, after eight months, in the following concepts: the requirements of plants, light and photosynthesis, photosynthetic organs in plants, purpose of photosynthesis, photosynthetic organisms, photosynthesis in eukaryotes, and the origin of the oxygen released during the photosynthesis. In the second year, pupils improved less than in the first regarding photosynthesis and respiration in plants. In the concepts related to photosynthesis in prokaryotes, the pupils regressed relative to the ideas with which they began the course.

One observes in Figure 3 that, in the tests given immediately after teaching the topic, the pupils did better on items corresponding to light and photosynthesis, photosynthetic organisms, and photosynthesis and respiration in plants in the first year when the teacher used a mainly technical/transmissive methodological approach. This improvement was transitory, however, only being sustained after eight months (Figure 4) in the case of photosynthesis and respiration in plants.

Discussion

(a) How does Ricardo's classroom practice evolve during the two years of investigation after participating in the action-research programme?

In the first year, Ricardo mostly took a technical/conventional methodological approach centred on the teacher's explanations. During this year, the largest group of actions were those which generated or reinforced the pupils' alternative ideas.

Ricardo's initial ideas were deeply rooted (Jeanpierre et al. 2005), and in the discussions on the analysis of the first-year classes it was difficult for him to reflect in any depth on questions related to the process of teaching and learning. As in other studies (da Silva et al. 2007), the catalyst for change was reflection on the pupils' ideas identified in the questionnaire. From that point onwards, the teacher showed himself to be highly motivated. This awareness was crucial for his internalisation of the need to involve his pupils in constructing their own knowledge and for his evolution from classes centred on the teacher's explanations to classes centred on the pupils' learning.

In the second year, Ricardo mostly took an inquiry/constructivist methodological approach centred on the pupils. At all times, he tried to take into account the pupils' ideas, putting forward a variety of activities and situations in the form of problems designed to generate cognitive conflict between his pupils' prior and new knowledge. The pupils needed to restructure their thinking for the new concepts to make sense and to be able to respond appropriately to the new situations. In this second year, there was a significant increase in Ricardo's actions aimed at facilitating the pupils' conceptual restructuring, and a concomitant reduction in actions that generated or reinforced their alternative ideas. As in other experienced teachers (Abd-El-Khalick 2006), in this second year Ricardo viewed photosynthesis as part of a larger picture, and we too believe that photosynthesis has to be approached as not only a cellular process, but as a broader process that resolves the nutritional problems of plants and other autotrophs.

(b) At the compulsory secondary education level, what are the pupils' alternative ideas about different aspects of photosynthesis?

In both of the study years, the pre-test given before the subject was taught identified the pupils' pre-existing ideas about photosynthesis. Many pupils did not consider the presence of minerals to be important for photosynthesis, with just the presence of water, carbon dioxide, and light being sufficient. They also considered that photosynthesis takes place only by day in the presence of sunlight, and that its main purpose is the production of oxygen. Indeed, teachers tend to speak about the sun when they are referring to the photosynthesis process. Even the textbooks usually have pictures of the sun in their illustrations representing photosynthesis. It is natural, therefore, for pupils to only associate sunlight with the process. Another common idea is that the principal purpose of photosynthesis is the production of oxygen, and that the oxygen released comes from the carbon dioxide molecule. These ideas may be reflections of an anthropocentric view of the world in the sense that plants produce the oxygen we need to breathe. Many pupils think of photosynthesis as 'inverse respiration' (Cañal 1999), an alternative idea that is reinforced when photosynthesis and cell respiration are taught as inverse phenomena. Indeed, one even commonly finds the following schematic representation of the two processes:

$$6CO_2 + 6H_2O \underset{\text{Respiration}}{\overset{\text{Photosynthesis}}{\rightleftarrows}} C_6H_{12}O_6 + 6O_2$$

This treatment of the content leads to an alternative conception in which plants perform photosynthesis by day and respiration at night. In the pre-test, the pupils considered plants to be the only photosynthetic organisms. This may be because teachers and textbooks always use plants as the example for photosynthesis.

(c) How do those ideas evolve as a result of the teachers' action-research programme? Is the pupils' conceptual evolution permanent or only temporary?

In the first year, the pupils showed an improvement in their ideas about certain of the concepts of photosynthesis. After eight months, however, their results showed a regression, in some cases returning to the initial, pre-existing ideas. The best results after eight months corresponded to photosynthesis in eukaryotes, and to photosynthesis and respiration in plants.

There was an improvement in the second year compared to the first after eight months in the following concepts: the requirements of plants, light and photosynthesis, photosynthetic organs in plants, purpose of photosynthesis, photosynthetic organisms, photosynthesis in eukaryotes, and the origin of the oxygen released during the photosynthesis.

Some of the pupils' results in the test given after the subject had been taught were better in the first than in the second year. The major difference was that in the first year, when Ricardo was taking a transmissive and rote-learning methodological approach, the improvement was transitory, with the results being considerably poorer after eight months. In the second year, when Ricardo took an inquiry/constructivist approach, at eight months the improvement was consolidated, with a lasting conceptual evolution of the pupils' ideas having taken place.

In the second year in both tests, the pupils showed less improvement than in the first with respect to photosynthesis and respiration in plants. Although the planning of this topic in the second year had followed an inquiry/constructivist model, it was insufficiently dealt with in the actual classes due to lack of time, which probably explains the pupils' poor performance. New data will have to be obtained on this concept in future research.

The poorest results in both years corresponded to concepts related to photosynthesis in prokaryotes. In these concepts, the pupils regressed relative to the ideas they had at the beginning of the course. The teacher had tried to promote the pupils' conceptual conflict with respect to whether or not chloroplasts exist in prokaryotic cells. In the end, however, he did not establish where photosynthesis occurred in these organisms. This could have contributed to the pupils' failure to evolve positively. These data suggest that the pupils' internalisation of these concepts would be helped by visual aids in the form of images and diagrams.

Final thoughts

A very important aspect throughout the study was that of the teachers' group meetings. The teachers' reflections on their pupils' commonest alternative ideas and on their own classroom teaching led them to plan new teaching units for the second year of the study which took those alternative ideas into account, and included new strategies, resources and activities. During the second year, Ricardo's educational treatment of the content, based on the interpretation of experimental data allied with an inquiry/constructivist methodological approach, helped the pupils' conceptual evolution in most of the concepts. Nevertheless, in most cases, there was no sudden replacement of the alternative ideas by scientific concepts, but a gradual process that took time and occurred in stages. The scientific ideas persisted for at least eight months in the pupils, suggesting that the learning was more meaningful, with a real evolution in the pupil's conceptual structure. Also detected was a hard core of the pupils' ideas which did not improve, and which requires further investigation.

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Appendix : Questionnaire

(This questionnaire is to collect data for an academic study. In no way is it an attempt to evaluate your knowledge, which is why it is anonymous.)

In the following questions, note just the one option that you think is most correct:

(1) To carry out photosynthesis, plants need:
____ Light, water, organic matter, and mineral salts.
____ Light, water, carbon dioxide, and mineral salts.
____ Light, water, oxygen, and organic matter.
____ Water, carbon dioxide, and mineral salts.
____ Light, water, and carbon dioxide.

(2) Plants perform photosynthesis:
____ By day only.
____ By night only.
____ By day and night.
____ By day and night, whenever there is light.

(3) Plants perform photosynthesis in:
____ All cells.
____ Above all in leaf cells.
____ Above all in cells of the stem.
____ In the cells of the root and stem.
____ In the cells of the root and leaves.

(4) The main purpose of photosynthesis is to:
____ Produce oxygen.
____ Produce organic matter.
____ Produce water.
____ Use carbon dioxide.
____ Produce glucose.

(5) Photosynthesis occurs:
____ Only in plants.
____ In plants and animals.
____ In plants, fungi, and some bacteria.
____ In plants, algae, and some bacteria.
____ In plants, fungi, and algae.

(6) In the eukaryotic cell, photosynthesis occurs:
____ Anywhere in the cell.
____ Only in the mitochondria.
____ Only in the chloroplast.
____ Only in the vacuole.
____ Only in the mitochondria and chloroplast.

(7) In prokaryotic cells, photosynthesis occurs:
____ Anywhere in the cell.
____ Only in the plasma membrane.
____ Only in the chloroplast.
____ Only in the mitochondria.
____ Only in the cytoplasm.

(8) Plants:
____ Do not breathe.
____ Breathe day and night.
____ Perform photosynthesis by day and breathe at night.
____ Perform photosynthesis at night and breathe by day.
____ Breathe only at night.

(9) The oxygen released in photosynthesis comes from:
____ The carbon dioxide molecule.
____ The water molecule.
____ The glucose molecule.