DEVELOPING MENTAL MODELS THROUGH VISUALISATION TECHNIQUES: AN EXPERIMENTATION ON THE SOLAR SYSTEM IN PRIMARY SCHOOL

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Abstract

The aim of this research was to investigate how the use of visualisation techniques can enhance the development and use of effective mental models in the context of astronomy education in primary school. Astronomy is a topic that fascinates children and poses didactical challenges at the same time. In fact, many astronomical systems cannot be directly experienced by the children and therefore need to be explored by means of models (mental, physical, graphical, etc.). While children spontaneously rely on imagination as a cognitive resource, mental images are seldom used explicitly by the teacher as a tool for learning, particularly in the field of science. In this work, we applied research results on the use of visualisation techniques for the development of mental models to the design of a learning unit on the Solar System. Using models is particularly necessary for addressing this topic, where children cannot rely on direct observation of most of the objects composing the system. To address our research question, we adopted a quasi-experimental design involving two fifth-grade classrooms, one of which represented the experimental group while the other one was the control group. The didactic units in the two classrooms were designed so that the use of visualization techniques was the only difference between the two groups and the interventions were conducted by the same teacher. The results showed a positive increase in both classes concerning knowledge about the Solar System, and that the technique used in the experimental group helped to strengthen the reference to models closer to the scientific ones.

Keywords: mental models, visualisation, solar system, astronomy, primary school.

1 INTRODUCTION

Astronomy has fascinated the humankind since its appearance on the Planet. Particularly in children's minds, the observation of celestial phenomena moves an infinity of questions. Children are available to look at the world and to imagine all the possible "worlds", sometimes introducing fantastic elements that allow great "abstractions" [1]. The most effective way to approach astronomy is through direct observation of astronomical phenomena that can be experienced locally, such as the day/night cycle, the seasons and the phases of the moon. Spontaneous observation of the sky should be followed or complemented by guided observations, using tools and instruments aimed at helping children focus on details and record and measure celestial phenomena. [2]. However, direct observation is not possible to the same extent for all astronomical phenomena. This is true for instance for large-scale structures such as the Solar System. Since children cannot directly see the Solar System as a whole from space, they can only rely on the local observation of some elements (the Earth, the Moon, the Sun, and some planets seen as distant lights in the sky) of the system and on its different representations (pictorial, physical, verbal, etc.). Moreover, when the dynamics of the Solar System is taken into account (which is necessary to explain the phenomena that children experience in their everyday life), the description reaches a high degree of complexity that is difficult to handle and represent [3]. Consequently, the study of many astronomical topics needs to be explored using models.

2 METHODOLOGY

2.1 Background

2.1.1 Mental models and images

In the description of physical phenomena, scientists often rely on models. Given the fundamental role that models play in science, they should also be considered an essential tool in science education. In fact, "Developing and using models" is one of the scientific practices identified as essential for science

education in the *K-12 Framework for science education* [4], according to which "[models] help develop explanations about natural phenomena [and] make it possible to go beyond observables and imagine a world not yet seen" [ibid., p. 50]. Among models, we can distinguish between mental models and conceptual models [4]. While mental models are personal, internal, incomplete and unstable, conceptual models are explicit representations that are in some ways analogous to the phenomena they represent. Conceptual and mental models are not independent and should not be considered as mutually exclusive: on the contrary, conceptual models can be seen as the external representation of the mental models held by the scientific community. Therefore, the development of scientifically correct conceptual models can be supported by the construction of improved mental models.

One essential characteristic of mental models is the use of mental images. Johnson-Laird [5] considers mental images as the language used for the construction of mental models. Visualisation - the ability to create mental images - is recognised by the educational community as a useful teaching tool as it supports the explanation, development and teaching of scientific concepts [6]. Despite its importance, visualisation is not usually the object of specific educational interventions in our culture [7]. As the schooling process goes on, imagination as a cognitive resource is gradually supplanted by logical-verbal thought. As a result, the effectiveness of mental images is weakened, in terms of frequency of use, image quality (including for example vividness) and ability to manipulate them [8]. In order to recover this ability, Statham [9] suggests rethinking four central aspects:

- Concepts as visualisations;
- Learning as awareness of visualisations;
- Progressions as restructuring visualisations;
- Teaching as using language that engages, enriches and deepens visualisations.

This training is particularly important when a conceptual model is difficult to approach because of the complexity of the contents and/or difficulties in the representation [10]. In fact, in a recent paper, Jankowska et al. [11] demonstrated that creative visual imagination can lead to improvements in children's understanding of astronomical concepts. A good example of an astronomical concept involving a model that is not so easy to understand is the Solar System.

2.1.2 Children's models of the Solar System

It is well known in Physics and Astronomy Education Research that children often come to the classroom with their own ideas and interpretations concerning physical phenomena, even when the study of those topics has not yet been dealt with formally at school. As many studies [12-15] pointed out, different models at different level of correctness can coexist incoherently. Referring to the topic of the intervention - the Solar System - one can ask what specific models the children refer to. Although the literature is rich in research on children's mental models about the Earth, studies about children's mental models of the Solar System are not as abundant.

A taxonomy of children's mental models of the Solar System was proposed by Sharp and Kuerbis [16], who conducted their research within the conceptual framework of mental models on astronomy proposed by Vosniadou [17,18]. The authors investigated the astronomical knowledge of children between 9 and 11 years of age using a structured interview and analysing children's drawings. They identified 9 mental models, ordering them hierarchically from the most scientific to the most intuitive:

- A - Heliocentric (complete/correct): Solar System includes the Sun and all the planets. Planets arranged in order, linearly or concentrically, and correctly named.
- B - Heliocentric (complete/incorrect): Solar System includes the Sun and all the planets. Some planets are arranged in incorrect order. Some names may be omitted.
- C - Heliocentric (incomplete/incorrect): Solar System includes the Sun and a selection of planets. Some planets are arranged in incorrect order. Some names may be omitted.
- D - Spiral: Solar System includes the Sun and all the planets. Planets arranged in order and correctly named. Planets appear to follow a "spiral" orbital path.
- E - Processional (Sun centered): Solar System includes the Sun and all the planets. Planets follow each other around the Sun on a single orbit.
- F - Geocentric: Solar System includes the Sun and up to 8 planets. Sun and planets orbit the Earth.

- G - Processional (Earth centered): Solar System includes the Sun and a selection of planets. Sun and planets follow each other around the Earth on a single orbit.
- H - Random: Solar System includes the Sun and up to eight planets (stars other than the Sun may also appear). All objects arranged at random. All objects stationary or move erratically.
- I - Earth – Sun – Moon: Solar system usually includes only these three objects. Earth orbits the Sun or the Moon, or all objects stationary.

Another study that investigated the topic was the one by Calderón-Canales, Flores-Camacho, and Gallegos-Càzares [19]. The researchers administered a semi-structured interview to 39 children from the first to the sixth grade of Mexican elementary school (between 6 and 12 years of age). Some questions required the students to simulate movements or build physical models of the Solar System using polystyrene balls. Using cluster analysis, the researchers identified six different models emerging from the interview: these models range from the simplest one, in which only the Sun, the Earth and the Moon are present as static elements, to the most sophisticated one, including the Sun, the Earth, the Moon, the planets, and some other elements such as stars or asteroids. As could be expected, the complexity of models increased with grade level.

One characteristic of all kinds of models is their flexibility, that is, the possibility to modify them [16]. Therefore, it is essential to consider the initial mental models possessed by students at the beginning of a didactic unit, in order to better choose the concepts to be taught and the learning experience that could promote this conceptual change [13].

2.2 Research design

The idea for this research started from an article by Statham [20], in which the author claimed that the eyes-closed methodology could enhance learning by helping children develop and strengthen scientific ideas and concepts. Referring to a constructivist paradigm, the author highlights how, although children's ideas are often formed during practical activities, the connection between these activities and conceptual understanding is not straightforward and cannot be achieved by practical activities themselves, as also expressed by Driver [15]. In a series of five articles [9, 20-23], Statham hypothesises that visualisation techniques can facilitate this connection in all the phases of a lesson, from the initial engagement to the final synthesis of the topic.

We identified the Solar System as the topic for testing Statham's hypothesis. This topic seemed particularly suitable for the experimentation, since children do not have direct experience of the Solar System except for their local perspective on its closest or largest elements; therefore, they need to rely on models to represent it. This topic is in agreement with the Italian curriculum for primary education [24], in which it is usually covered in the fifth grade, and it is also one of the core ideas of Earth and Space Sciences in the *K-12 Framework for Science Education* [4].

In particular, our research addressed the following question*: How can visualisation techniques support the development of a scientifically correct model of the Solar System?*

To answer this question, we designed a didactic unit on the Solar System containing several visualisation activities as suggested by Statham [20]. We adopted a quasi-experimental design involving two parallel classes, of which one was designated as the other as the control group.

2.3 Participants

The classes involved in this study were two fifth-grade classrooms of a primary school located in Padua, Italy. Each group was composed of 21 pupils: 9 boys and 12 girls in classroom A (experimental group), and 12 boys and 9 girls in classroom B (control group). As far as could be established, the two groups had remained stable over time and their educational backgrounds were very similar. The same teacher conducted the intervention in each of the two groups.

2.4 Assessment

For the assessment of the intervention, we referred to the work by Sharp and Kuerbis [16]. The authors proposed a structured one-to-one interview that contained 12 items, regarding the main components of the Solar System, their size, their movement and location in space, their age and origin. Based on this work, two tools were developed and administered:

- For the pre-test, a semi-structured, one-to-one interview lasting about 5 minutes, where the interviewer was allowed to make use of probative questions (reformulation of the question or answer, request for further explanation) and non-verbal language in the case of uncertainty. The interview also included the request of a drawing of the Solar System.
- For the post-test, a written questionnaire with open questions, parallel to those posed during the interview, including the drawing of the Solar System. The choice of this instrument rather than another interview as the post-test was due to the organisation constrains of the hosting school.

The answers were scored using a range from 0 to 3, where 0 corresponds to “I don’t know/I’m not sure” and 3 indicates a good knowledge close to the scientific one. Since the focus of the intervention was the development of models, the drawings were the object of a specific evaluation. The models emerging from children’s drawings were classified according to Sharp and Kuerbis [16].

3 DESCRIPTION OF THE LEARNING UNIT

The intervention included 6 lessons of two hours each for the experimental group (12 hours) and 5 lessons of 2 hours each for the control group (10 hours). The difference relates only to the activities that envisaged the use of visualisation techniques, while for all the other aspects the structure and content of the activities were the same for both groups. Below is a brief description of the proposed activities: the ones that were carried out for the experimental group only are reported in italics.

Table 1. Activity plan.

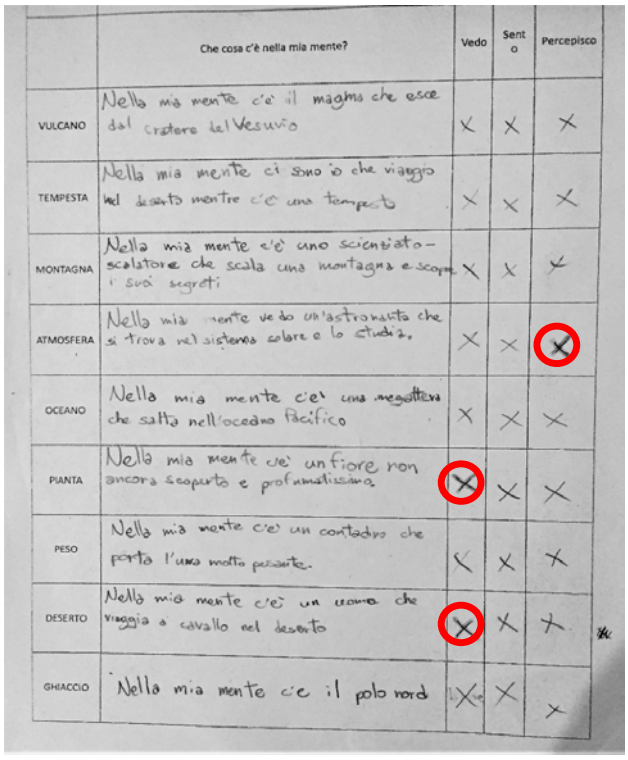
Lesson no.	*Goal*	*Activities*
1	Detect initial children’s ideas	Pre-test (interview)
2	Introduction to the topic and to the technique	• *Eyes closed for stories* • *The cat sat on the mat* • My terrestrial environment • Words to describe the terrestrial environment
3	Improve the quality of mental images and connect them to reality	• *Enriching our words* • Garden exploration • *Journey in the terrestrial environment*
4	Explore the Solar System	• Solar System jigsaw • *Journey through the Solar system*
5	Assess children’s models of the Solar System	• Our Solar System • Distances in the Solar System
6	Assess final children’s ideas	• *Eyes closed to reflect and review* • Post-test (written)

In the following we provide a more detailed description of the activities.

- Lesson 0. Pre-test: the children were interviewed one-to-one according to the protocol outlined above.
- Lesson 1. The following activities were proposed:
  - “Eyes closed for stories” (experimental group only). The teacher told a story from her life related to the topic, using words and expressions with strong visual, auditory, and kinaesthetic (VAK) meaning and gradually switching from the “I” language pattern to the “you” language pattern [22, 23]. The children were asked to keep their eyes closed throughout the story.
  - "The cat sat on the mat” (experimental group only). With their eyes closed, the children were asked to listen to the sentence ”The cat sat on the mat” and then describe what they had seen in their minds [9]. As expected, different images emerged. This experiment helped

children become aware of their mental images and how they can be different from one another.

- “My terrestrial environment”. The children were asked to close their eyes and imagine the terrestrial environment. At the end, they made a drawing representing what they had imagined.
- “Words to describe the terrestrial environment”. The children closed their eyes while the teacher pronounced some words related to the terrestrial environment (volcano, storm, mountain, atmosphere, ocean, plant, weight, desert, ice). For each of them, they described what they had seen in their mind, indicating if it is a word that they mainly see, hear, or feel (Fig. 1) [21].



	Che cosa c'è nella mia mente?	Vedo	Sento	Percepisco
VULCANO	Nella mia mente c'è il magma che esce dal cratere del Vesuvio	X	X	X
TEMPESTA	Nella mia mente ci sono io che viaggio nel deserto mentre c'è una tempesta	X	X	X
MONTAGNA	Nella mia mente c'è uno scienziato-scalatore che scala una montagna e scopre i suoi segreti	X	X	X
ATMOSFERA	Nella mia mente vedo un'astronauta che si trova nel sistema solare e lo studia.	X	X	X
OCEANO	Nella mia mente c'è una megattera che salta nell'oceano Pacifico	X	X	X
PIANTA	Nella mia mente c'è un fiore non ancora scoperto e profumatissimo	X	X	X
PESO	Nella mia mente c'è un contadino che porta l'uva molto pesante.	X	X	X
DESERTO	Nella mia mente c'è un uomo che viaggia a cavallo nel deserto	X	X	X
GHIACCIO	Nella mia mente c'è il polo nord	X	X	X

Figure 1. Mental images and word enrichment with VAK data.

- Lesson 2. The following activities were proposed:
  - “Enriching our words” (experimental group only). For each of the words considered in the previous task, the children were asked to close their eyes and focus on their mental images while the teacher guided them through specific scaffolding questions in order to add the "missing" sensory data [21]. The red circles in Fig. 1 represent the missing sensory data that were added with this activity.
  - “Garden exploration”. The children were free to explore the school garden with the aim of gaining a concrete experience of the terrestrial environment.
  - “Journey to the terrestrial environment” (experimental group only). Sitting in the garden and with their eyes closed, the children listened to a story about a journey in the terrestrial environment. The story was constructed using the words analysed previously and paying attention to VAK data. The children were then asked to produce a new drawing of the terrestrial environment (Fig. 2).

Figure 2. Drawings of the terrestrial environment before and after the visualisation activities.

- Lesson 3 and 4. The following activities were proposed:
  - “Solar system jigsaw”. The children explored the components of the Solar System using resources from the school library, in a jigsaw classroom environment. Each “expert group” prepared an "identity card" of one of the objects of the Solar System.
  - “Journey through the Solar System” (experimental group only). With their eyes closed, the children listened to a story describing a journey through the Solar System. The story was constructed paying attention to VAK data and to the I-we-you shift.
- Lessons 5 and 6. The following activities were proposed:
  - “Our Solar System”. Back in their jigsaw groups, the children built their own physical models of the Solar System (Fig. 3).
  - “Distances in the Solar System”. Using the IWB and Google Maps, the teacher reflected on the scale of distances in the Solar System, using references from the area around the school.

Figure 3. One of the physical models of the Solar System produced in the jigsaw activity.

- Lesson 7. Post-test
  - "Eyes closed to reflect and review” (experimental group only). The children were asked to close their eyes and imagine the Solar System; then, they reported their mental image in a drawing.
  - Post-test: the children were asked to complete a written questionnaire with parallel questions as the ones asked during the pre-test.

4 RESULTS

The pre- and post-test results for the two groups are presented. For the analysis, two aspects were considered: the total scores in the pre- and the post- test and the evolution of mental models as they emerged from the children's drawings.

4.1 Total scores

4.1.1 Experimental group

A comparison between the pre-test and post-test is provided in Fig. 4.

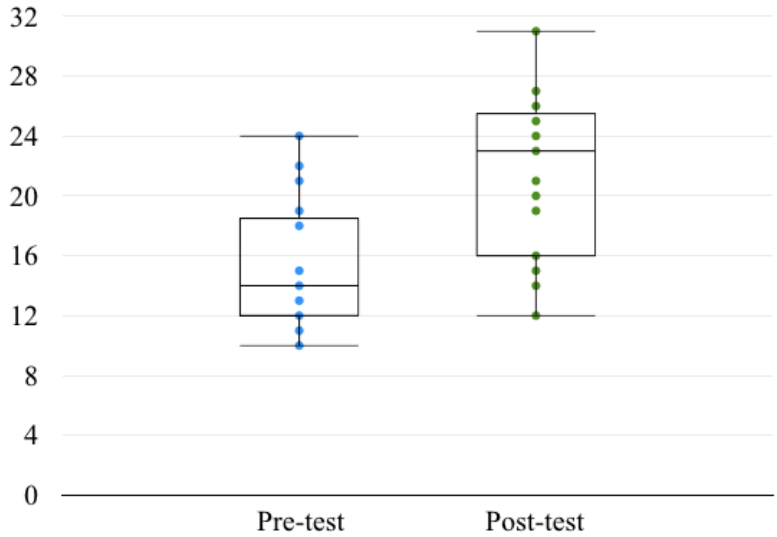


Figure 5. Box plot of the pre- and post-test score distributions, experimental group.

In the pre-test, individual total scores ranged from 10 to 24, with an average of 15 and a standard deviation of 4. Two groups of children emerged: a large one(15 children) with scores between 10 and 15, and a smaller group (6 children) with scores higher than 18. In the post-test, individual scores ranged from 12 to 31 with an average of 21 and a standard deviation of 5. A Wilcoxon signed-rank test showed that the intervention produced a statistically significant change in the scores ($Z = -4.0145$, $p < .00001$). Indeed, the median was 14 in pre-test and 23 in the post-test.

4.1.2 Control group

A comparison between the pre-test and post-test is provided in Fig. 5.

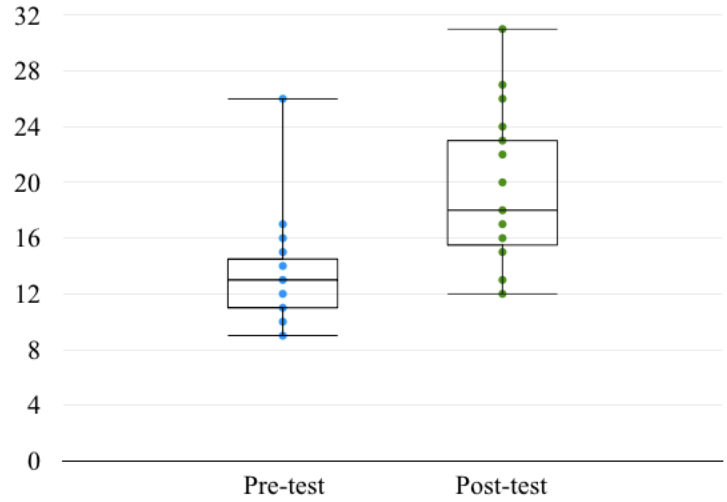


Figure 5. Box plot of the pre- and post-test score distributions, control group.

In the pre-test, the individual total scores ranged from 9 to 26, with an average of 13 and a standard deviation of 4. The distribution was symmetrical, with most of the children scoring between 9 and 14 and a single child who received very high score (26). In the post-test, individual scores ranged from 12 to 31 with an average of 19 and a standard deviation of 5. The median was 13 in pre-test and 18 in the

post-test. A Wilcoxon signed-rank test showed that the difference in pre- and post-test scores was also statistically significant ($Z = -4.0145$, $p < .00001$).

4.2 Models of the Solar System

Individual drawings of the Solar System produced in the pre- and in the post-test were classified according to [16] and compared, as reported in Table 2.

Table 2. Evolution of mental models of the Solar System.

Model	Experimental group		Control Group	
	Pre-test	Post-test	Pre-test	Post-test
A - Heliocentric (complete/correct)	4 (19%)	16 (76%)	1 (5%)	12 (57%)
B - Heliocentric (complete/incorrect)	5 (24%)	5 (24%)	0 (0%)	3 (14%)
C - Heliocentric (incomplete/incorrect)	10 (48%)	0 (0%)	9 (43%)	4 (19%)
D - Spiral	0 (0%)	0 (0%)	0 (0%)	0 (0%)
E - Processional (Sun centered)	1 (5%)	0 (0%)	2 (9%)	0 (0%)
F - Geocentric	0 (0%)	0 (0%)	0 (0%)	1 (5%)
G - Processional (Earth centered)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
H - Random	0 (0%)	0 (0%)	9 (43%)	1 (5%)
I - Earth-Sun-Moon	1 (5%)	0 (0%)	0 (0%)	0 (0%)

4.2.1 Experimental group

In the pre-test, 19 out of 21 children (90%) referred to a heliocentric model (A-C), even if it was incorrect and/or incomplete (B-C) in most cases. Post-test drawings suggested that all the children have reached a heliocentric model, which was correct and complete (type A) for 16 (76%) of them and complete and almost correct for the remaining 5%.

4.2.2 Control group

In the pre-test, two prevalent models emerged: the C model (heliocentric, incomplete/incorrect) and the H model (random model), both used by 9 children (43%). Only one child provided a complete and correct heliocentric model (A). In the post-test, 19 children (90%) referred to a heliocentric model, which was correct for 12 (57%) of them. Two children were still referring to non-heliocentric models, specifically the geocentric model (F) and the random model (H).

An example of the mental model evolution for a pupil in the experimental group is provided in Fig. 6.

Figure 6. Drawing of the Solar System by pupil DE (exp. group) before and after the intervention

5 DISCUSSION

For both groups, there was a statistically significant increase in the scores. While a similar increase was observed in the average score between the two groups, a higher increase was obtained in the experimental test for the median (8 points vs 5 points in the control group). Concerning the models of the Solar System held by the children, both groups reported a positive development, to a higher extent in the experimental group.

Comparing our results with those obtained by Calderón-Canales et al. [19], we found many similarities, but also some differences. In particular:

- Most children refer to the planets as the components of the Solar System;
- In general, children have little perception with respect to the distances between the objects;
- With respect to the motion of the objects in the Solar System, we found a greater awareness of the simultaneous presence of rotation and revolution compared to the literature;
- With respect to the models of the Solar System held by the children, we observed a more frequent use of correct models.

Therefore, in our case, the visualisation technique has contributed most of all to improving the mental models of the Solar System in favour of more scientifically correct ones. However, in agreement with Vosniadou et al. [25], we are aware that the old models may continue to coexist together with the new ones. Following the approach by Sharp and Kuerbis [16], a more reliable assessment on the effectiveness of the intervention could be done by repeating the assessments some months after the conclusion of the intervention, in order to verify the persistence of correct models.

From a didactical point of view, the use of visualisation techniques had some relevant advantages, specifically:

- Ease of use: visualisation techniques could be used in any phase of a lesson, they required little preparation and no special resources.
- Limited time cost: activities involving visualisation techniques required 5 to 10 minutes per lesson, thus not significantly affecting the amount of time allocated for the topic.
- Positive mood: especially when visualisation techniques were used at the beginning or at the end of a lesson, they contributed to a relaxed atmosphere and an engaging environment.

However, when using visualisation techniques, attention must be paid to some issues. First of all, the success of these techniques is dependent on the teacher's involvement and control over his/her communication; a lack in these aspects may result in an obstacle to children's attention [20]. Moreover, the best of this approach can be obtained from a systematic work, where children get used to the technique and refine their ability of producing effective mental images [21]. As Mathewson [3] suggested, the best would be obtained by including visualisation techniques in initial teacher training.

6 CONCLUSIONS

Our research suggest that visualisation techniques can foster the development and use of effective mental models of the Solar System in fifth-grade pupils. Besides its value for science education, we think that this technique has a global educational value as well. In a world where children are subject to thousands of visual stimuli every day, we believe that reflecting on the images we see when we close our eyes and using them for learning is a precious experience.

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