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FROM THE ASTRO TO THE NANO SCALE: A LEARNING BY DOING TEACHING PATHWAY

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ABSTRACT. From the nano-world to solar systems length-scales span over several orders of magnitude. In young student it is therefore hard to fully understand the relative proportions among different objects even belonging to the same level of complexity. Resizing to human-related distances is an effective way to understand the relative distances in astronomic scales or the amount of information contained in a single cell. In general, the use of imagination is essential in educational research as well as the use of different skills in interdisciplinary works. Some appealing example will be given and the result of a pilot learning by doing teaching pathway involving hundreds of young students will be presented. Clues will give indications for future directions in educational research.

1. Introduction

Since the introduction of the telescope and microscope in the centuries 18^{th} and 19^{th}, we have been forced to reconsider the relativity of the scales and, what is probably more important, our perception of the world. It was Galileo with his astronomical observations using his handmade telescope who struggled to change the geo-centric model for the heliocentric one (Strano 2009). On the other hand, it was Antonie van Leeuwenhoek, who pioneered coupling lenses to achieve hitherto unheard of magnifications and considered the father of microbiology, the one that saw for the first time what he called "*animalcules*" in just a drop of water. These were nothing more than bacteria, blood cells and other tiny microorganisms swimming around but never seen before (Lane 2015). These new realities clashed with the established idea of size scales and were rejected, even catalogued as heresy. Nowadays, the development of new technologies allowed us to go even further and we are able to observe distant galaxies or exo-planets at the astronomical level and biomolecules and proteins at the nanoscale. However, these conceptions are still not embraced, and it is sometimes a though task to make people, and especially pupils, understand the concept of size and, most notably, its relativity. Moreover, when teachers in school talk about scientific-related topics, especially those ones that involve "inconceivable" magnitudes as the previously noted astronomy or nanotechnology, it is sometimes easier to understand the more complicated theoretical concepts than to realize and take in mind the 'real' sizes and distances present in those fields. In our daily life, the words small and big are used constantly and, it seems like everything needs to be seen to be made up with accuracy in our mind. For that reason, placing the concept of size into another perspective, more obvious and familiar for students could make them understand more easily some concepts of how big or small things are, regarding astronomy and especially nanotechnology.

Some scientific books such as "*The odd book of data*" (Houwink 2014), where facts and their figures regarding topics such as physics, biology, energy "and economics" are put in a more achievable perspective so the reader can have a real idea about their magnitude. Well-known novels such as "Gulliver's Travels" (Swift 1950) also played with this idea when Gulliver travels to the Lilliput island and to the Brobdingnag peninsula, being the small and big perspectives, respectively. There are even scientific papers (Mattice 2008) describing the main idea of this approach in order to make easier to understand concepts or even processes.

The completion in Spain as well as in Italy of the workshop called "From the astro to the nanoscale: which is bigger?" is presented in this publication as a learning by doing teaching pathway to make students from 6 to 11 years comprehend the real sizes of planets and macromolecules, such as DNA. This will be made by thinking about them with another perspective, making such length scales more easily comprehensible to a human mind that is far better adapted to dealing with relatives than absolutes. Consequently, this approach has two main objectives. First, it could be considered as a way to push the introduction and implementation of new student-active learning (*i.e.*, learning by doing) methods. Secondly, this workshop can be considered as a good introduction to a reasonable way of thinking and to the experimental methodology, before bringing pupils to move towards their first steps in experimental sciences like physics, chemistry, biology and natural sciences in general.

2. MERGING small and big: complexity and imagination

2.1. The ternal Problem of Size. It is firstly important to put the students into the mindset of understanding sizes and making them a match for being well understood. As a starting point, there is a simple question to be asked: what seems big to you? And, on the other hand, what would be in comparison something small or smaller? Usually, this places the students in perspective, and they answer instantly and one by one, being even able to say something bigger or smaller than what has been previously said by a classmate. However, it is very important to make them realize that the scale of sizes they are using or the concepts they have in their minds are really limited and, even sometimes, tricky. As the French philosopher Nicolas Malebranche wrote while discussing the impressions and judgements we make about the sizes of things under our eye-perception, "*Car rien n'est grand ni petit en soi*", which means that nothing is either large or small in itself (Malebranche *et al.* 1982). For that reason, the very first example to make them think about this will be by showing them a map and asking for the real size of the countries. As Earth is round, its representation on a flat surface as maps necessarily distorts countries. The key lesson of this is that there is always the need to ask ourselves everything, because even that which our eyes can clearly see may not be objective reality. Moreover, it is important to make students realize that observation plays a crucial role in science and it is the basis of the scientific method. However, as our technology is being improved, the blurry line between the observable and unobservable moves and what was once ‘unobservable’ can become ‘observable’ now.

2.2. Complexity bridges small and big. Elementary particles are somehow assembled to form atoms (physics), atoms are assembled to form molecules (chemistry), molecules can be assembled to form living cell (biology), opportunely organized living cells can constitute tissues (physiology, medicine), and so on, organs, human beings, ecosystems... in a multi-step escalation which can have a big number of levels. Sticking to the examples given in this manuscript, this is schematically depicted in Figure 1.

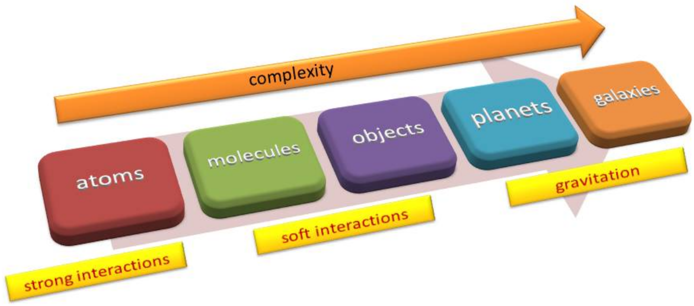

FIGURE 1. Levels of complexity in a wide length-scale range. Some typical interactions are highlighted.

Some system of fundamental building blocks, interacting by a set of defined rules is a principle which underpins a range of fields of study, from chemistry (atoms/electrostatic forces) to sociology (humans/societal forces). However, if the building-blocks are independent and non-interacting, their assembly would be just a simple aggregation. The behavior of the system could be predicted from the characteristics of each building block. On the other hand, if the constituents are interacting, the final assembly is not the mere collection of “units” and the overall properties cannot be obtained by simple extrapolation of the characteristics of their constituents. New and sometimes unexpected properties can arise when passing from one level of complexity to another. In this case the system is said to have complex behavior. It is worth to underlining that it is not only a matter of size, but whether the building blocks are interacting or not. Interactions are therefore needed to have assemblies and therefore definite objects to compare. In the investigation of matter the interactions are can be chemical, electrostatic, magnetic (Peddis *et al.* 2014) in all their variety (Gale and Steed 2012). This variety of interactions induces an enhancement of the complexity and increases the ways in which multicomponent systems can interact, but also enlarges the range of the structural nano and meso-morphologies possible in everyday life materials like liquids, suspensions, colloidal aggregates, biological systems (Kiselev *et al.* 2008, 2013) and can extend, although not directly visible, to gravitational effects for astronomic distances.

In this framework, a unique comprehension of the phenomena related to the nano- and astronomic distances needs interdisciplinarity. The European Union itself promotes interdisciplinary education (Feather and Aznar 2010).

It must be noted that sometimes the complex pattern has fractal structures, *i.e.*, with auto-similarity patterns at different length scales, a characteristic very common both at a molecular structure level (Lombardo 2014) and at a macroscopic one in soft matter (Bonaccorsi *et al.* 2013; Stein *et al.* 2013). Such peculiar structural behavior also inspires modern artists due to its fascinating features.

2.3. The role of imagination. This approach cannot help but consider imagination and intuition as the driving forces. Imagination, in fact, despite heated century spanning debates, has been recognized as a pivotal ingredient in science. Jacobus Henricus Van't Hoff (1852-1911) himself, one of the pioneers in suggesting the use of imagination in science since his "*The role of imagination in science: van 't Hoff's inaugural address*" dated 1960 (Benfey 1960) is aware that science has an aim, (*i.e.*, to find the relationship between causes and effects) and, in this search, imagination cannot but having a pivotal role, a belief fully shared by other famous scientists after him like Richard Feynman (1918-1988) (Feynmanl 2013) In finding the relationships between causes and effects van't Hoff individuated two steps:

- the observation of a phenomenon;

- the search for cause-effect relationship.

Imagination is essential first of all in the former step not only in the choice of the exact moment (and nature) of observation, but also in the careful choice of the observation experimental conditions in order to have a more significant inspection. However, imagination is essential also, and probably more evidently in the search for the link between causes and effects, exploring the most opportune, even if sometimes indirect, pathways.

We like to state that imagination is essential in developing a hypothesis bridging the previous knowledge with the new and still to be reationalized phenomena. This process is schematically depicted in Figure 2.

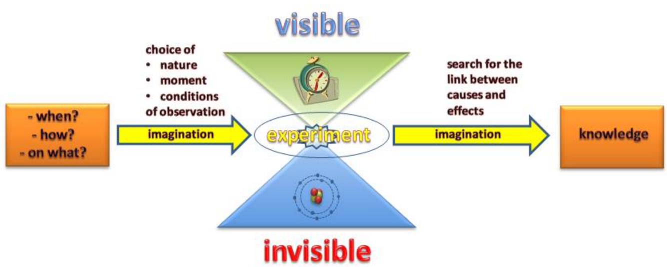

FIGURE 2. Re-adaptation of Van't Hoff's belief in on the role of imagination is science.

In accordance with this idea, the presented learning pathway has therefore been designed for young students beforebefore move them towards experimental activities in natural sciences.

Planet	Real Diameter (km)	Downsizing diameter (cm)	Model	Downsizin Mean Orbit (m)
Sun	1.39 · 10^6	2.433	-	-
Mercury	4.878	0.9	Corn tomato	101
Venus	12.100	2.1	Cherry tomato	189
Earth	12.756	2.2	Cherry	262
Moon	3.500	0.6	-	1
Mars	6.786	1.2	Blueberry	399
Jupiter	143.200	25.0	Watermelon	1.360
Saturn (without rings)	120.536	21.2	White cabbage	2.238
Uranus	51.118	9.0	Tomato	5.017
Neptune	49.528	8.6	Apple	7.867
			*Orbit around	the Earth

TABLE 1. Planets in the Solar System with their true and relative sizes.

3. Making the big smaller: planets reduced to Fruit sizes

It is generally instinctive to think of the Universe when we are thinking about something really big. This sense of immensity has characterized humankind from its beginning. However, we are still not aware of its real size. Young students (<10 years old) study the planets and their satellites in the Solar System. Yet, they are not completely aware of the sizes and distances between them. If we consider, for instance, the Earth and the moon, they have diameters of about 12800 and 3500 km, respectively. In order to make them more conceivable, we can imagine our Earth as a basketball, which is around 25 cm. By the proportion shown in equation (1),

$$scaled\ size\ of\ moon = \frac{size\ moon}{size\ Earth} size\ basketball = \frac{12800\ km}{3500\ km} 25\ cm = 7\ cm \quad (1)$$

we can calculate the size of the moon in this scale, which turns out to be 7 cm, approximately that of a tennis ball.

When children were asked, before showing both balls together, most of them answered that the Earth was bigger than the moon. However, the more inaccurate answers were given when they were asked to place the two celestial bodies at their relative distance. All of the students thought the distance that separates the Earth and the moon was less than it really is. Given its dominance of the night sky, it is natural to think the moon much closer than it really is. But again, these distances are not really clearly seen by our eyes and all of the students were surprised to see that on this scale the earth and moon, should be separated 7,6 m, which in a standard classroom it is almost from one side to the other.

The same procedure could be done to obtain the relative sizes of all the planets in the Solar System when the Earth is considered now as a cherry tomato of 2.2 cm. The relative sizes of all the planets are shown in Table 1 and, with some imagination, we can correlate these sizes with the fruits shown in Fig. 1.

The students were aware of the sizes when planets were compared, and they can say which ones are bigger or smaller. However, it was clearly surprising for them to discover the real relative sizes when planets such as Jupiter or Saturn are put together with the cherry tomato Earth. Although it was not discussed in detail with the students, the distances between the planets were also mentioned taking the Sun as the starting point. Of course, this is a more problematic point to be shown in a classroom, as the distances in our Solar System are considerably bigger: if the Sun is placed somewhere in the classroom, Mercury would be at 101 meters, surely out of the classroom. On the contrary, the farthest planet, Neptune, which is situated at 4.504.300.000 km away from the Sun, would be an apple almost 14 km away. If we speak about our planet Earth, which is situated 146.600.000 km away from the sun, in our new system it will be 262 m away from the class. And still, there is a question that makes students even more impressed. This is related to the fact that all these distances are filled with nothing but the vacuum of the space. Children and adults could be shocked with the fact that our solar system is almost completely empty. Most common question is how we can be sure about these astonishing distances. In this regard, parallax can be explained if needed (Marr 1997).

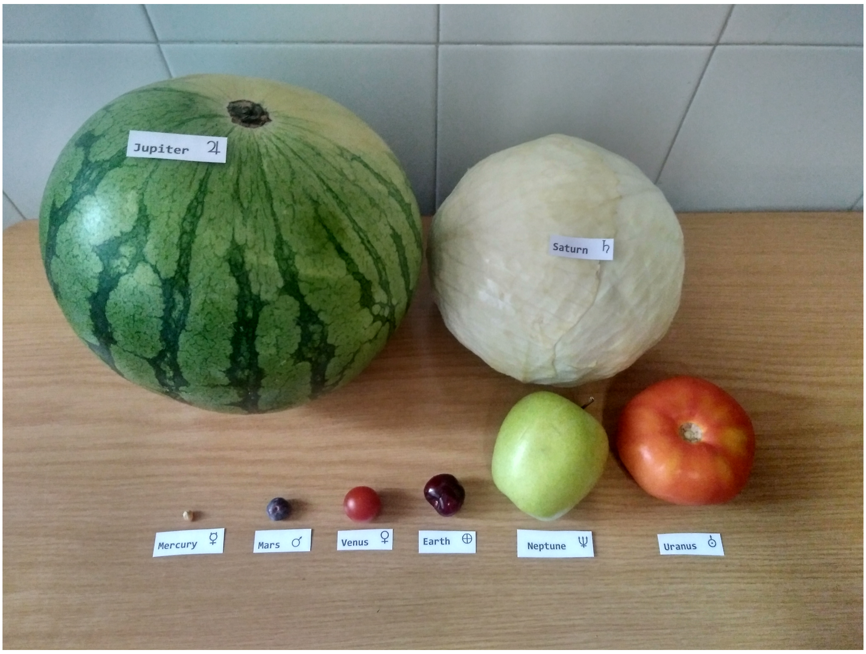

FIGURE 3. Planets represented as fruits or vegetables models according to Table 1.

4. Making the small bigger: molecules enlarged to be seen

The main objective of this work is to make more understandable to students the sizes that are not considered in our normal daily life but more related to science. After having presented the relative sizes of the planets and their distances apart, it is now time to look down. There was a pioneer on this, who was the great physicist Richard Feynman, who could be considered as the father of nanotechnology. His speech "*There's Plenty of Room at the Bottom*" asks questions before conceived (Feynman 1992). In fact, at that time nobody had ever questioned the 'staggeringly small world that is below'. Although nanotechnology today is present in our lives in more ways than we are even aware of, it is typically used only in scientific environments. Let's make students consider how small the things in nanotechnology are. For example, cells, the basic units of life, can have sizes between 1 μm and hundreds of micrometers. We are still not in the nanoscale, but it is more useful for students to get closer to the nanoscale little by little. It is interesting to note that students in elementary school usually define cells as small things that cannot be seen by naked eyes. However, cells can be as large as an egg. Indeed, eggs are the largest cells on Earth. The ostrich egg is as big as the size of a melon. If we go now to the human body, the female ovum is around 0.1 millimeters, the size of a sand grain. On the other hand, the human spermatozoon is almost three times smaller. It is made by a head and a flagellum that is 8 times bigger than the head. This is the clue: understanding the typical relative distance between ovum and spermatozoon allows the parallel understanding of the spermatozoon's peculiar structure.

In fact, if these dimensions are resized in such a way that the ovum is a tennis ball (diameter 7 cm), it turns out that the spermatozoon is a cherry (about 2.2 cm) but more interestingly the typical distance between the two cells (*i.e.*, when the egg is situated in the Fallopian tubes) being around 12 cm is resized to 48 km! This is quite a long journey, so, on its way to fertilize the ovum, the spermatozoon needs such a long flagellum to propel itself. Now it is more understandable why the spermatozoon needs such a big propulsion to arrive to its target.

Both the ovum and the spermatozoon carry inside them half of the genetic information that will give rise to the offspring. The genetic information is contained in an organelle inside the cell, called the nucleus of approximately 10 μm, in the form of a double-helix polymer 10 nm thick, *i.e.*, 100 times smaller. DNA and other bio-related molecules making part the cells are in the nanometer range.

So let's move to the nanoworld.

Pupils between 6 and 11 years old still don't know a lot about the DNA. However, this could be a good opportunity to explain to them its function by saying that DNA contains the so-called "genetic information": they dictates our height, colour of eyes and hair and all the rest. Use the metaphor "book of life" written with an alphabet of four letters only, known as "base pairs": guanine, adenine, thymine and cytosine, which are put together in a particular way, known as a double-stranded helical chain.

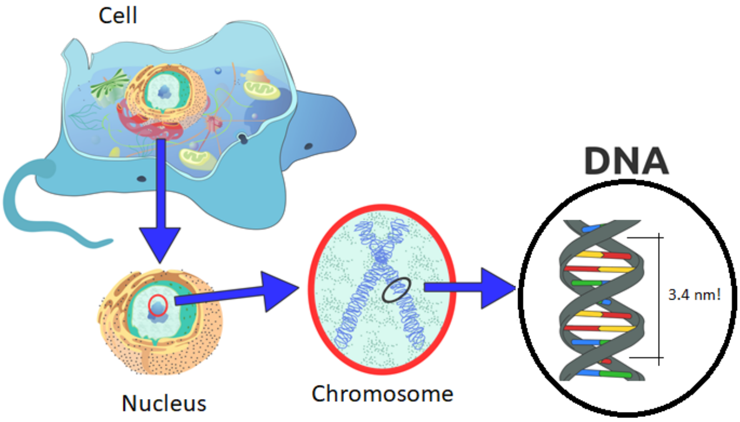

FIGURE 4. Schematic representation of a cell, its nucleus, a chromosome and the DNA present inside this last one, with the size of an entire loop of the double helix strand. Image adapted from Wikimedia Commons.

There are around 3 billion letters (base pairs) in this book of life. The distance between two adjacent letters along the helix axis is about 0.34 nm. If each cell carries in its nucleus 6 billion base pairs, as they have in one strand and its complementary, the length of the total DNA inside it will be calculated by multiplying this value of base pairs by the longitude of each base pair as follows:

$$6.000.000.000\, base\, pairs \times 0.34 \cdot 10^{-9}\, m = 2.04\, m \tag{2}$$

A single cell in our body carrier about 2 m of DNA! Furthermore, some estimations say that our body contains about 3.7 × 10^{13} cells (Bianconi *et al.* 2013). The total length of the DNA that a human has in his body is then given by:

$$\frac{2.04\, m\, DNA}{cell} \times 3.7 \cdot 10^{13}\, cells = 7.55 \cdot 10^{13}\, m \tag{3}$$

This estimation works out that the total DNA present in a human being, is about 75.500 million km long! Considering, as stated in the previous paragraph, that the distance between the Earth and the Sun is 146.600.000 km, it turns out that if all the DNA in our body is spread like a rope in direction to the Sun, we could be able to go and come back for almost 260 times! Or even we could arrive from the Sun to the last planet Neptune and back for about 8 times! This is due to the extremely small sizes involved in the nanoscale.

5. An experiment to make macromolecules visible

It is now time for a small and simple experiment, where the classroom is divided into groups of four/five students. The pupils can do it themselves, with the supervision of each of the teachers, by following the instructions given and thinking about why each step and the different processes are done. The main objective of the experiment is to make elementary school students comprehend that because of the large number of cells present in living things and because each of them carries the same DNA inside, if we are able to extract all the DNA from each cell, it will become big enough to be visible to the naked eye. But this is not the only one. This experiment has also as an objective to bring closer and make students more familiar with experimental procedures and protocol, usually followed by scientists, but without going too deep in the biochemical considerations. However, the students should be able to critically think about the basic operations needed in order to achieve our goal, which in this case is to extract and see the DNA. It should be underlined that the described experimental procedure can be realized just using commercial easily available materials.

5.1. DNA extraction from a banana. The following elements will be needed to do the experiment:

- A glass
- A zipped plastic bag
- A ripe banana
- Mineral Water (warm if possible)
- A pinch of salt
- Dishwashing soap
- Paper filter
- Ethanol (it will be better if it is coloured and cold, so you can add some alimentary colouring and put it in the fridge priori to use)
- Toothpicks

The procedure followed is explained below, as well as the concepts that should be taught to the students. Take in consideration that each step needs time to be performed. Be patient and let the compounds interact with each other for some minutes.

(1) The banana is peeled and placed in the plastic bag. As the highest possible number of cells needs to be exposed, the banana needs to be chopped into smallest pieces possible. For this purpose, the bananas are then smashed inside the bag until a paste is obtained.

(2) Then, DNA needs to be extracted. As shown before, it is inside the cells and, in turn, it is inside the nucleus. Something is therefore needed to break up the cells and make possible for the DNA to escape. For this reason, in the glass half full of warm water a pinch of salt is added and then removed with the toothpick to get it properly. Then, it is added to the bag and gently mixed with the smashed banana by hand-shacking. A bit of the dishwashing soap is also added to the bag and mixed again carefully, taking care of not to form foam. It will be the soap which will be in charge of breaking up the cell membranes and its nuclei. This is because such

membranes they are made of opportunely oriented lipid compounds (**12**); Kiselev *et al.* 2001) whose structure is well known to be susceptible to interactions with organic molecules (Lombardo *et al.* 2018). In particular, the interactions involving *amphiphilic block copolymers* can be so peculiar that structural change can take place even with a reduced number of molecules (Lombardo *et al.* 2019), giving cell membrane rupture if these species are strong enough like those in a soup are used. On the other hand, the salt will be in facilitate the DNA strands sticking to each other in clumps large enough for being seen.

(3) Once the DNA is out of its cellular ‘cage’, it needs to be separated from all the molecules still present on the plastic bag. For this, water is filtered to get rid of the pulp of the banana. A filter is placed on the top of the glass and the paste is poured on it. It must be shown to the students that the filter is composed by fibers forming a network, with very small spaces. As the water and DNA is smaller than these spaces, they can go through the filter dripping down into the glass. Then, the filter with all the remaining things will be discarded.

(4) Once the water with the DNA inside is obtained, something needs to be added to make it visible, because now, as it is dissolved, it cannot be seen. For this purpose, as DNA is not soluble on ethanol, alcohol is slowly added to get a thick layer of on the top of the liquid banana mix. After waiting for about 8 minutes some cloudy material should start appearing. Using the toothpick all the DNA obtained can be picked. It will be like a gummy white stuff (see Figure 5).

FIGURE 5. Glass with the alcohol – water solution containing the clumps of DNA extracted from a banana when the previously described protocol was followed by the students. It is a real image from the workshop realized in Sardinia (Italy) during the Science Week Festival that took place in December 2017.

6. Impact of leaerning pathwhay

The proposed learning pathway , far from being intended as a canonical lecture, is to be thought as a dynamic way of understanding, experiencing and learning how to furnish to young students a first approach to the scientific way of thinking and methodology. Hence, the interaction with the pupils is the pivotal factor. The proposed learning pathway in a form of a workshop has been carried out four different times, at the time of writing this paper. One of these was performed during the 2017 Science Week Festival in Sardinia, Italy, where more than 100 students ranging from 7 to 16 years old assisted (See Graph 1 in Figure 6). After completing the activities, the students were asked to fill out an easy test questionnaire not involving specific or arduous questions: if they like school and their favorite subject. The results are summarized in Fig. 6 graphs 2 and 3. It can be noted that more than 80% of the pupils enjoy school (at least they wrote so!) while the preferences of the subjects were divided more or less fifty-fifty between the classical divisions of scientific and social sciences.

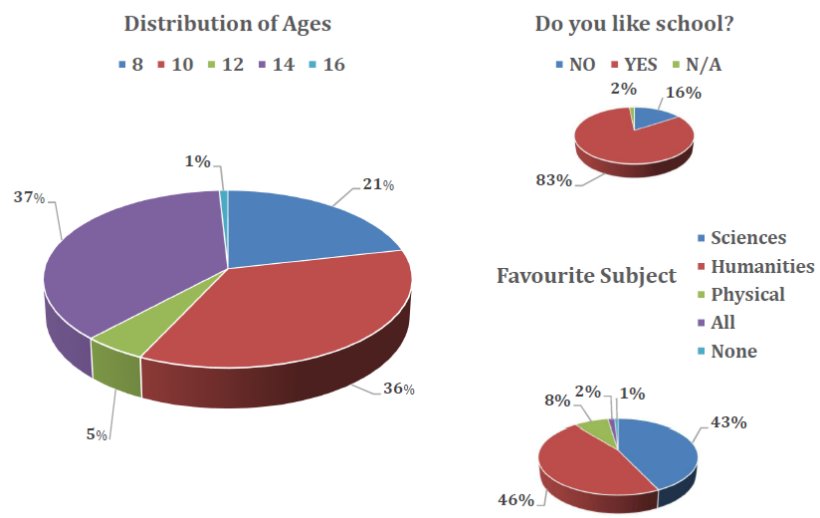

FIGURE 6. Data obtained from the questionnaire done during the workshop.

The questionnaire also contained the following questions regarding the workshop itself:

(1) Why are relative the dimensions of the things?

   (a) Because our eyes are different

   (b) Because it depends on the reference system used

(2) Does DNA have a particular shape?

   (a) Yes, double-helix
   (b) Yes, it is like a cloud
   (c) Yes, it is like a braid
   (d) No

(3) What is the effect of the soap on the cells of the banana?
   (a) It cleans them out
   (b) It makes them more beautiful
   (c) It breaks the principal bonds among the cells
   (d) It kills them

Such questions were intended to give an idea on the understanding of the general concepts given during the workshop. Regarding the first question, 95% of the students answered that there is the need to stablish a reference system to compare different objects. This idea was well introduced by the re-scale of the different planets and its location in the Solar System. On the other hand, it was only 64% of the pupils answered that the DNA has a double helix shape while 45% answered it had a braid-like shape. Although there were some pictures shown during the workshop, the double helix shape is still difficult to be pictured in the mind of the students and it could be confused with a braid. Maybe there is the need to incise harder here, by maybe showing real models of DNA. This points out that the more real and touchable experiments or demonstrations you perform during this kind of activities, the easier the students take in the concepts. Finally, in the last question, the understanding of the experimental method was examined by asking what the purpose of adding the soap in the DNA extraction was. Here, 80% of the students agreed with the fact that it was to break the bonds inside the cells while 20% agreed that it was to kill the cells. Somehow all of them have their reason, as the goal of the soap is to break the bonds among the cells, so in anyhow kill them.

7. Conclusions

This work shows a learning patway base on learning by doing approach, to give pupils between 6 and 11 years some insights about the concept of size and its relativity in experimental sciences and scientific things. It could be seen as a trip from the astronomic things to the nanoscale, where the relativization of the sizes of different objects in both opposite scales should make the children wonder about how we perceive the world and its real size. It is also a first approximation to a scientific experiment. Students will be able to do it by their own because of its simplicity, but thinking about the methodology that is being followed in order to achieve the goal of the experiment. The size of the observable Universe and elementary particles could be considered as an advanced continuation of this work.

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