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Enhancing mathematics and science learning through the use of a Human Orrery

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We present in this paper an innovative approach to introduce STEM topics in the classroom through the context of the Solar System. Our pedagogical tool consists in a Human Orrery modeling at a human scale the Solar System dynamics. While learners walk along planetary orbits, they enact different mathematical and scientific notions. Previous experimentations were centered on science concepts and have shown an enhanced motivation and well-being and a better understanding. We discuss here the connection with the cognitive science theory of enactivism and with the activity theory, both already used in the field of mathematics education. New pedagogical sequences are proposed that deeply combine mathematics and science contents. Those will be set up in a classroom context before the CERME conference.

Keywords: Astronomy, enactivism, instructional innovation, STEM education.

Introduction

STEM literacy is a crucial issue for European educational policies today as emphasized by successive trans-European studies since the Rocard report (2006). Numerous difficulties have been revealed by science and mathematics education researchers in knowledge acquisition of scientific notions of movements, velocity, proportionality and functions. Many of them arise from the gap between children's sensorial or everyday life experiences and the abstract scientific explanations.

The study presented in this paper explores the use of astronomy to teach mathematics and physics. We consider that astronomy should not be taught and considered in education science as an independent subject but as a specific application of general laws of physics and of application of mathematics concepts. The European ROSE project (Sjoberg & Schreiner, 2010) has shown that the subject that interests both girls and boys was found to be life outside earth. We confirm in our experiments that the study of the Solar System motivates students to do sciences, while a large number of mathematical subjects may be easily introduced through the observation and understanding of planets' motion. The tool that we use to this purpose is a Human Orrery modeling at a human scale the Solar System dynamics in ways that can enhance the learner's perception of mathematics and physics concepts in a real world apparatus.

In the following sections, we will provide a description of this tool and its affordance and the potentials within a STEM approach. We will also present our theoretical frame and the outcomes of first preliminary experiments. This background presentation enables us then to introduce a large scale project in progress and to give some examples of settings that are being currently designed in order to be implemented, observed and evaluated in several European countries.

The Human Orrery

An Orrery is a mechanical instrument showing circular orbits of the planets. The first Orrery to be created at a human scale was done in Japan (Dyonic Astropark) and then at the Armagh Observatory (Asher, Bailey, Christou, & Popescu, 2007). The design of a Human Orrery is made such that users may walk along orbits of different bodies around the Sun that is located at the center of the design. The Human Orrery that we use is printed in a large map of 12m by 12m (see Figure 1). It allows one to follow the orbits of the inner planets (Mercury, Venus, Earth and Mars) and Jupiter; the inner planets are located inside the asteroid belt that is materialized with a grey color together with the orbit of the largest asteroid known, Cérès. The highly eccentric orbits of two comets are also used: Encke (the smallest elliptical orbit) and Chury. This choice of objects illustrates different type of movements while keeping the size of the Orrery reasonable. Earth is at one meter from the Sun, while Jupiter's orbit has a diameter of 10,5m. The orbits of all bodies are materialized by dots at constant intervals of times, with accurate elliptical shapes. Note that, orbits are near-circular for the five planets and Ceres.

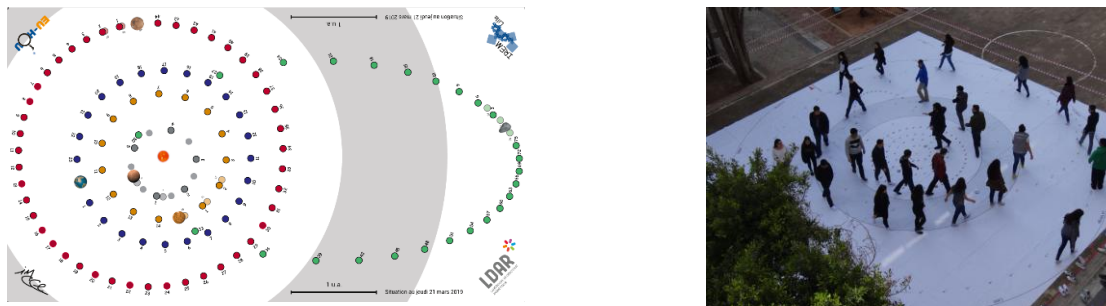


Figure 1 – Left: The map of the Human Orrery (inner planets and one comet only, see text for details). Right: Pupils walking along the different orbits up to Jupiter.

The interval of time may be different for each orbit, but is always a multiple of 16 terrestrial days: For Earth, there are 23 dots separated by 16 days, which would make a period of 368 days. For Jupiter, there are 54 dots separated by 80 days, which makes a period of 4320 days instead of the real period of 4332,59 days. A sound (either a clock or hand claps) is heard regularly. The interval of time between two sounds corresponds to 16 terrestrial days. Every user makes one step during this time interval. Then, the person that enacts Earth walks from one point to the next (distance) in one step (duration), while “Jupiter” has to do five steps (five times 16 days) to reach the next point. All rules are described in details in Rollinde (2017). By acting according to those rules, the movements on the Human Orrery illustrate the correct relative velocities of all Solar System bodies.

Both constructing and enacting on Human Orrery involve topics from mathematics and science and enhance a STEM approach of scientific notions usually perceived as abstract concepts by students. We shall discuss in more details the use of the Human Orrery and its future perspective for STEM education after a discussion of the theoretical framework underlying this innovative pedagogy.

Theoretical framework

The use of a Human Orrery in education is based on the assumption that bodily perceptions help the learning of abstract concepts. In other words, “abstract symbols used in formal education—words and syntax in reading, numbers and operators in math—need to be grounded in bodily experience”

(Glenberg, 2010). In the context of the Solar System, the objects under scrutiny can neither be touched nor seen directly in the classroom, duration is very long, and very little is expected to happen in the classroom situation. By physically enacting the objects and their movements, the situation changes completely: dynamic properties are revealed and experienced; the invisible and impalpable acquire a certain degree of “palpability” allowing learners to deeply understand them as walking along the Human Orrery.

The cognitive science theory of enaction (Varela, Thompson, & Rosch, 1991) may provide a theoretical foundation to those assumptions. Torrance (2005) describes enactivism as the nature of the mind, defined by its relation to the world: “(...) the organism’s world is “enacted”, brought forth by sensorimotor activity: world and organism are co-determined, they co-emerge. [For the mind], awareness of its self and of its world is a central feature of its lived embodiment in the world.” Transposed into Mathematics Education (we refer the reader to the review by Reid, 2014), enactivism theory has been used successfully, for example to explain the emergence of formal mathematical thought from pre-mathematical experiences in the course of a lesson sequence on three-dimensional geometry for 6-year-old children (Roth, 2011). Similarly, in the context of a numerical sequence, Radford (2014) shows that, “through an intense interplay between various sensorial modalities and different signs, the students’ perception and the concomitant mathematical thinking have gained a theoretical dimension that they did not have before”. More generally, learning can be facilitated to the extent that lessons are created that map to and activate sensorimotor systems (see for example Johnson-Glenberg, Megowan-Romanowicz, Birchfield, & Savio-Ramos, 2016 in the context of digital platforms).

This line of argument may sound contrary to early researches in science education that rather tend to show that our observations and interactions with the world often produce naïve conceptions in conflict with formal physical laws (e.g. Hestenes, Wells, & Swackhamer, 1992). Difficulties in knowledge acquisition in science seem to arise from the gap between children’s sensorial experiences and the abstract scientific explanations. We make here the assumption that it is necessary to promote a “mindful attention to perception” (Varela et al., 1991). In the context of the Human Orrery, our goal is to build a complex learning world filled by metaphors: a simple map becomes the empty interplanetary space; series of dots become the elliptical structure of an orbit; peers become planets with different velocities; duration is heard while distance is felt... The Human Orrery (a human-scaled technological object) acquires a meaning through the learner’s cognition and his/her mindful perception of this world and thus activates new cognition.

To theoretically ground our observations, analyses of teaching and learning within the Human Orrery context we plan to make use of Activity Theory as used today in Mathematics education (Abboud et al., 2018; Vandebrouck, 2012). Roth and Jornet (2013) acknowledge that original works on Activity Theory by “Soviet social psychologists explicitly ground their ideas in theories in which thinking, acting and environment are part of the same analytic unit.” Indeed, the Activity Theory, in particular the notion of subject-object interactions mediated by an instrument enables to study the activities of subjects (teachers and learners) using tools (the Orrery itself but also the set of technological tools involved) and their impact on the processes of learning physical and mathematical concepts at stake when experiencing the Human Orrery. Yet, current use of Activity

Theory in education does not mention the role of bodily perception. “Mental processes (speaking, thinking, reading or writing) need to be understood in terms of complex ecologies: neuromuscular and physiological processes AND cultural historical origin and nature” (Roth & Jornet, 2013). Our intention is thus to work towards an “Embodied Activity Theory” which would be a framework adapted to our research and that would develop over time in a dynamic interaction between analyses of data and design and use of theoretical tools.

Outcomes from first experiments

The main use of Human Orrery in the literature has been the introduction of astronomy in open schooling contexts (e.g. Asher et al., 2007; Francis, 2005; LoPresto, 2010). Since 2014, our team focuses on the use of a “human Orrery” to learn science rather than astronomy only in different pedagogical context, from primary school to University. Through our initiative, seven Human Orreries were built in France (one for a science center, one in a public place in Paris, five in primary or secondary schools), one was drawn in a Lebanon school and one map was purchased by a science center in Vietnam. Human Orreries are used thereafter by different teachers (physics, mathematics, technology and sports) in those seven places plus about five other schools who use our trap only. Questionnaires and interviews were used to quantify the amount of learning and the students’ motivation. The sequences are discussed and improved after each application. They have also been used in teacher education for two years, and may be obtained upon request to the authors. More details on these first experiments and derived conclusions as described here may be found in Rollinde (2017).

The implemented sequences have focused on the one side on the motivation and interests of the learners and on the other side on specific scientific notions. Among the key concepts introduced through the Human Orrery are kinematic ones. The embodiment of duration and length allows to alleviate the confusion related to the use of those concepts in the common language. The manipulation of those two concepts to compute the velocity requires to deal with three variables, which is known to be source of cognitive overload. As an example, almost every groups express a confusion between large velocity and small orbital period, or between small period and small perimeter; they all reduce the reasoning to a simple comparison between two variables. The enaction is expected to lighten the abstract mathematical task by providing diverse sensory-motor experiences as proposed in the sequence described in the next section. Additional difficulties encountered regularly include: the Moon that cannot be seen given the scale used (she would be behind the disc of the Earth); the confusion between 24h and one year for one orbital period of Earth (which is strengthened by the 23 dots used for the orbit of Earth); the very low speed of Jupiter is also a source of astonishment. Comments made by undergraduate students actually showed their surprise that so much may be learnt with this tool. For instance, one student declares: “There was joy, emotions. Here, it is wonderful what is going on’. She continues then: ‘Universe is not made of mathematics numbers and equation of physics, this is something else, and it has to be understood in another way.” Another student suggested that “illustrating a concept with a movement makes it more real. We feel that we live it.”

Project and examples of settings

The authors of this paper aim at incorporating more STEM contents into future works. We propose in the following an example of such settings, that we are currently designing, tackling the study of speed's meaning and proportionality factor. More examples could be given particularly concerning the construction of the Human Orrery and associated mathematical notions at play, but this goes beyond the scope of these proceedings.

A detailed enacted sequence on speed

In the science class, speed is understood as the length of a displacement for a given time unit (e.g. year or second). This sequence will provide a way to enact three concepts (time, distance and speed) using bodily perceptions and tools. In the mathematic class, speed is understood as the proportionality factor in the relationship between distance and duration. Ayan and Bostan (2018) have shown that proportionality relationship is often approached by superficial characteristics of the problems, namely the monotonous relation expected between two variables, and lack clear, quantitative, arguments. Modestou and Gagatsis (2010) express the metacognitive aspect that underlines the awareness of (non)-proportionality and may explain this lack of coherence in reasoning about proportionality. There is thus an obvious need for a renewed approach to proportionality and speed.

The sequence we designed uses the Human Orrery, a clock that sounds regularly (each sound is called a clap) with a given tempo, blue ropes and red ropes and markers (to materialize different positions along the ropes). There are four stages: (i) Enaction of space and time while walking freely on the Orrery under spatial and time constraints. (ii) Following a right planetary walk to enact different displacements for different durations. (iii) Enaction of the speed of the planets and the proportionality relationship. (iv) Determination of the speed of the planets (optional). The first two stages can easily be implemented in primary school; the second two are more adapted to lower secondary school.

Enact space and time

The initial proposed goal is to invent a coherent way to walk on the Human Orrery. The action is then to walk, while focusing on two perceptions: looking and hearing. The students' task explained by the teacher may be: "you have to find a way to walk coherently while accounting for dots on the map and claps. At the end, you will have to explain your choices." We expect that different rules may be proposed. For instance, each step should last the duration between two claps or each step should go from one dot to the next one, whether the students focus on what they hear or what they see. According to the rules proposed, we seek for answers to questions such as: Are they going to make a connection with speed too? Are they going to use local rules (their steps only) or global rules (the entire orbits or their relation with each other)? Are they going to describe what they are doing or global observations (who is going faster or when to end)? All those possible and expected actions (or wording here) will be useful to understand what is enacted and how.

According to the effective actions, different proximity-in-action (Abboud et al., 2018) may be foreseen to ensure coherence among the group. The students' activity could either remains on a

minima level e.g. by proposing to focus on one set of dots that follow one orbit or at on a maxima level, e.g. by going faster or slower and to propose different ways to use the rhythm or the dots

Enact the planets' movement

The first action will probably end up with different solutions for a coherent walk. In the process, most learners should have noticed that the drawing is related to the Solar System. The teacher confirms and describes the different orbits. The learners want to know and understand their own role in this planetary walk. The next goal is then to measure their movement while walking as planets.

The associated task requires organisation and mathematical skills: "You will work by groups of 3. Each group chooses either Earth or Jupiter. You start to walk when you hear one sound and continue to walk until you hear "n" additional sounds. You must then find a way to show to the entire class the length of your displacement in order to compare or combine the different measures". The number "n" is explicitly given but is different for each group. For Earth, some group will work with 3 claps, some with 7 claps. For Jupiter, some will work with 5 and some with 9. Those numbers are chosen so that none is a simple combination of others by the use of addition, in order to favour the use of multiplication later on. To achieve this task, each group has a rope (blue for Earth and red for Jupiter) and markers that can be attached to the rope.

Due to the complexity of the task (follow the rules, do not measure the line but the circular length, keep record of the measured length for comparison), specific proximity-in-action are required to go through it. First, every group has to respect the planetary rules. Then, the length of a circular displacement will be measured with the rope and some markers. For groups that have completed the first task, the teacher may propose to measure the distance while starting from another point in the same orbit or to do the same measurement for another orbit with a different rope. It is important to ask them to walk and measure simultaneously, in order to enact the displacement together with the duration.

Enact the proportionality relationship between length of displacement and duration

To keep the learners focused on the subject of planets, the next goal is directly related to planets while the action will be made on ropes only. By this shift, the reasoning is made slightly more abstract. The required task is not a physical action but a reasoning one in order to answer the question: "how do the speeds of Jupiter and Earth compare?" This may sound like a simple task if it was a simple account of what they have played. Indeed, it is to compare the speed of Jupiter and Earth during the planetary walk. To avoid this shortcut, the teacher asks for a material, or visual, proof using the ropes. This reformulated task becomes complex and fully associate science and mathematics skills and concepts.

A first prediction may be searched for: How should the length of the rope of the faster planet compare to the slower one (a minima)? Such a comparison requires using a common duration, or the same number of sounds. This is our first sub-task. Let's call N the common number of claps associated to this common duration. N may be equal to 10 (this number may be obtained with the available lengths through the sum of $7+3$ for Earth and the product $2 \text{ times } 5$ for Jupiter).

The next sub-task is then to derive the length that would have had the rope of the two planets for this common duration. The teacher proposes then to measure the length of the displacement after one clap only. To realise this task, one has to divide the rope in N parts and then use the ruler... or use the ruler for the full length of the rope and divide by N !

Enact a non-proportionality relationship

Exposing learners to a non-proportional situation is a way to face the well-known bias of proportionality and to encourage students to develop a critical mind. The Human Orrery provides us with an interesting situation: the case of a comet. Unlike the planets' orbits which are near-circular, the orbit of the comet Encke is a highly eccentric ellipse. During the movement on its orbit, the speed of the comet varies strongly: learners have to make either very large steps near the Sun or cannot even put one feet between two dots far away from the Sun. This usually creates either laugh or stress but never leave the learners insensitive in that case, duration and travelled distance are thus related monotonously, but are not proportionally linked. Using the same methodology as for Earth and Jupiter, learners will discover that the length of the rope measured for different initial position and different duration is not proportional to the duration.

The examples of pedagogical sequence that we presented above are the first of a set of settings that will be designed and implemented in several countries and in different cultural contexts as part of a European project we are currently setting up. We note that activities on the Human Orrery may also be used as an introduction to more formal mathematical activities; for example, on the derivation of Kepler laws using power laws and interpolation or on the understanding of Newton laws using differential equations.

Conclusion and perspectives

The perspective that we adopt in our project is that of STEM being taught through an interdisciplinary approach that incorporates an embodied dimension and draws on real-world modeling. The use of the Human Orrery enables students to enact or “experience” scientific concepts and the dynamics of their properties by evolving in an adapted environment. Until recently, we only focused on the dissemination of Human Orreries and on a proof-of-concepts in terms of motivation and interest. Different sequences have been co-constructed by teachers and researchers and have led to preliminary positive results on learning too. The current dynamic of the project is to motivate more classes from different levels and teachers from subjects other than mathematics and physics such as art, technology, music, languages (native or foreign), physical education and sport. In 2018-2019, four additional classes have decided to join the project in France: two primary schools in the context of interdisciplinary projects and one secondary school through a project on Mars involving science and technology. At the European level, we are expecting to submit a H2020 project involving research in mathematics and science didactics together with science centers (museum, observatories and associations). Our next objective is then to design sequences that fit into the STEAM approach and that will be used as experimental situations for the theoretical framework of enactivism, complemented with the framework of Activity Theory in the context of science education. Our focus will be as much on the didactical learning as on the motivation and awareness of the learners during the activity.

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