# Learning Science Through Enacted Astronomy

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## Abstract

The Human Orrery is a representation of the Solar System at a human scale, on which positions of planets over time are symbolized by different discs. Learners can then walk along the orbits of the planets with the right pace. This pedagogical tool uses the principles of enacted cognition to promote a better understanding of the scientific laws of dynamics. Enaction assumes that cognition is based on action. Applied to pedagogy, it implies that learning of concepts must be based on gestures and perceptions first. I applied during two years an enacted pedagogical sequence using our Human Orrery to different populations of learners. The main purpose was the understanding of velocity and inertia by KS4 classes (14-16 years old). Interviews and closed questions reveal a qualitative enhancement of the motivation and well-being of the learners during the enacted sequence. To evaluate further the impact of the enacted sequence, I formulated two open questions. The first one concerns the relation between distance, duration and velocity through the period of planets. The second one focuses on inertia and gravity through the comparison of the free fall of an apple on Earth and the orbit of the Moon around Earth. The questions were asked to KS4 pupils after the enacted sequence (experimental classes) and to KS4, undergraduate and pre-teachers after a classical lecture on dynamics (demonstration classes). Quantitative analysis of the answers reveals specific cognitive insight, especially for students reasoning about velocity and trajectories. The general purpose of this paper is thus to illustrate the use of the Human Orrery in the context of science education in the classroom and to make a first, preliminary demonstration of its efficiency.


*Keywords*: Enaction, Human Orrery, Science education, Solar System, Velocity

## Introduction

The research presented here focuses on science education with astronomy as the medium, and enaction (Varela et al. 1991) as a theoretical framework. More specifically, a Human Orrery allows the setting up of an enacted Solar System, with a focus here on embodied notions of velocity and inertia.

The Orrery is a representation of the Solar System. Initially, an Orrery is a mechanical instrument showing circular orbits of the planets around the Sun. The first Orrery to be created at a human scale was done in Japan (Dynic Astropark) and then at the Armagh Observatory (Bailey, 2006; Asher et al., 2007). The Japan one used circular orbits, while Armagh Orrery is a very accurate representation of the elliptical orbits including comets. The human Orrery that I use was granted by Sorbonne University and designed by N. Rambaux and P. Rocher (researchers in the Institute IMCCE, Observatoire de Paris) following the model of the Armagh Observatory. Printed on a large tarp, one may bring it to any schools by car! This article shows the conclusion of a pedagogical sequence repeated for three consecutive years, making 14 years old pupils walking on the Orrery (Figure 1).

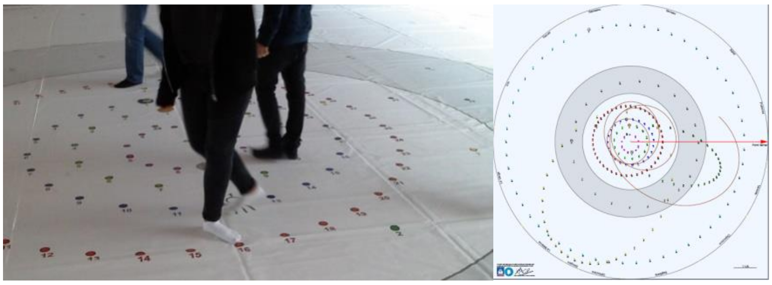

***Figure 1.*** **The Human Orrery. *left:* A walk on the Orrery. *Right:* the 12mx12m Human Orrery**

The Sun is at the center of this Human Orrery, with a spatial scale of 1 meter for 1 AU (Astronomical Unit). The bodies of the Solar System that can be enacted with the Orrery are the inner planets (Mercury, Venus, Earth and Mars) and Jupiter; the largest asteroid known, Cérès inside the asteroid belt (represented with a thickness of 1 AU between Mars and Jupiter); and two comets, 2P/Encke and 67P/Churyumov-Gerasimenko. “Chury” has been revealed to the general public since the European Spatial Mission Rosetta. Earth is at one meter from the Sun, while Jupiter's orbit has a major axis of 10,5m. The surface of the Orrery is of 12m over 12m. The orbits of all bodies are elliptic, but near-circular for the five planets and Ceres.

Along each orbit, the positions of the different bodies are materialized by discs at constant intervals of time. This duration may be different for each orbit, but has to be a multiple of 16 terrestrial days. For Earth, there are 23 discs separated by 16 days, which would make a period of 368 days. Every year, there will be an offset related to the real period (similar to the principle of the bissextile years). Details of the rules for each orbit will be given in the description of the pedagogical sequence. What the reader should retain from this is that any group of persons may walk on the Orrery and enact thus the planet's movement with correct relative speed. Topics such as inertial movement, velocity-distance, force-velocity relation, that are known to be difficult, can be refined and perceived by the learners' body. The connection between mathematics and physics appears in many different cases: observation of the elliptical orbits (geometry), discussion about scales and properties of planets (powers of ten, proportionality), velocity as a ratio of length and duration (and as a vector), construction of relations (graphs, power laws), change of referential and movement of Mars (positions in a 2D map)… Additional ideas (focused on astronomy rather than on physics) may be read in Francis (2005), Asher et al. (2007) and on the web(1), or discussed through direct inquiry to the author.

My first intention is not to bring astronomy to schools as an exciting subject, regardless of its scientific content and its relation to the curricula. It is to allow pupils to learn about science, mathematics as well as physics, in a context that will interest them, through their body as well as their mind. To emphasize this position, I give in the first section an overview of the theory of enaction applied to pedagogy. The scientific knowledge to be learned through the proposed pedagogical sequence is introduced next, together with two open questions defined to investigate the associated level of understanding; I then define the different classes and schools that were involved in this project. After a full description of the sequence that was set up and applied during three years, I analyze the answers to the open questions and to other feedbacks more centered on pupils' and learners' reactions to the enacted sequence. I finally conclude with propositions based on the results of this work to go further in the evaluation of the level of science understanding and of well-being for the learners, and in the learner's true embodiment during the sequence.

## Enaction or Embodied Cognition

Surprisingly, the fact that we are experimental physicists since birth interferes with learning formal basic physics concepts. We bring to the learning experience well-entrenched ideas based on our observations and interactions with the real world, but those experiences do not easily allow us to separate effects of multiple forces (e.g. gravity, friction, and centrifugal forces) which can produce naïve conceptions that are often in conflict with formal physical laws (Halloun and Hestenes, 1985; Lakoff and Johnson, 1999). Most of the time, difficulties in knowledge acquisition arise from the gap between children's sensorial experiences and the abstract scientific explanations. It is then necessary to address scientific misconceptions through new channels, and particularly through a "mindful attention to perception" in line with the work of Varela et al. (1991).

The theory of enaction claims that our mental model building is interconnected with our perception of the external world through all our senses. Cognition arises then through the dynamic interplay of brain controlling bodily action controlling perception, which changes the brain. This theory focus on the importance of action and how action shapes perception, the self, and language. As a consequence, new abstractions need to be grounded in some physical reality or perceptions to be fully understood. This is particularly true for the youngest and the learning of fundamental concepts such as reading (Glenberg 2015) or mathematics (Segal, 2011; Kim, Roth, & Thom, 2011; Abrahamson et al., 2016). Kinaesthetic modelling has also been used successfully to understand astronomical geography (Slater, Morrow, & Slater, 2008), moving frames (Plummer et al., 2011, 2014) or astronomical trajectories through a human Orrery (as in this work and works cited in the introduction). Along this line of argument, Frappart et al. (2014) assumed in the introduction of their work that children would first understand gravitation in the earth context because only there can they observe and experience it directly. In the spaceship and moon contexts, given that children would need to rely on cultural mediation processes for their information, they expected to see only a gradual improvement in their predictions and none at all in their justifications (which was confirmed in their work).

Embodiment theory applied to education implies that learning can be facilitated to the extent that lessons are created that map to and activate sensorimotor systems. Goldin-Meadow et al. (2001) propose that gesture and speech form an integrated, synergistic system in which effort expended in one modality can “lighten the load on the system as a whole,” that is, gesturing may actually shift some of the load from verbal working memory to other cognitive systems. Mina Johnson-Glenberg and Ken Koontz (embodied-games.com) define embodied games as:

> Content that is both kinesthetic and multimodal. This means you are encouraged to use gestures, or to move your body, and that multiple senses or modalities will be activated during learning. An important idea associated with gesture-based learning is that the gestures be “congruent to” the content to be learned. Evidence shows learners retain more information when sensori-motor areas of the brain are activated. Adding the sensori-motor trace to the usual visual and auditory traces in the brain strengthens the memory and makes the learning truly multimodal.

In the context of astronomy, I have designed a sequence that maps the Solar System dynamics and learner's perception in a real world apparatus, the Human Orrery. Before a complete description of this sequence, I provide the reader with a description of the scientific knowledge that will be mapped, and of the methodology used for the evaluation of the learning.

## Overview of the Research

### The Targeted Concepts of Physics

The designed sequence focuses on two fundamental notions related to the KS4 curricula (14-16 years old pupils) in France. An open question is proposed for each notion in order to assess the existence of conceptions and to evaluate the level of understanding. The scientific answer and the quantification of this level is discussed in the section named “Evaluation”.

The first notion is the velocity, associated to notions of space and time. Those are studied since the very early school period, in particular in the French curricula (Coquidé & Morge, 2011). The main focus is on the relation between velocity, distance and duration. For an object that goes from a point A to a point B, it reads:

$$t_B - t_A = \frac{D}{v}. \quad (1)$$

In this relation, D is the length of the path (that is not necessarily a straight line), $t_A$and $t_B$ are the instants when the object is on A and B respectively, and so $t_B - t_A$ is the duration of the trip. I consider here movements with a constant absolute value of the velocity. That amounts to considering circular orbits only.

The associated open question is:"Explain why Jupiter takes more time than Earth to go around the Sun." (original question in French : *Expliquez pourquoi Jupiter met plus de temps que la Terre pour faire le tour du Soleil*).

The second notion is inertia and gravitational attraction. The objective is to consider the relation between force and trajectories. I was thus looking for cases with similar forces, but different motions.

The associated open question is: “Explain why an apple falls on the surface of the Earth while the Moon orbits around the Earth " (original question in French : *Expliquez pourquoi une pomme tombe sur la surface de la Terre alors que la Lune tourne autour de la Terre* ?)

The formulation of this question may sounds more problematic. Indeed, the referential frames for the two situations are not explicit, and are likely to be different. The apple trajectory is naturally thought in the terrestrial frame, while the orbit of the Moon would rather be in the geocentric frame. Yet, I believe that specifying the referential frame would not help the reader. Besides, the difficulty resides not in referential frames, but rather in the co-existence of two different trajectories while the direction of the force is the same (towards the center of Earth).

Those concepts, namely velocity, inertia, and gravitation, are hereafter called the “targeted concepts” of this work. Cognitive difficulties about those are known and well-studied (Ebersbach, Van Dooren, & Verschaffel, 2011; Planinic et al., 2012; Lee & Park, 2013; Roorda, Vos, &  Goedhart, 2015; see also discussion in the Supplementary Electronic Materiel, SEM). The objective of this work is to get a first evaluation of the impact of an enacted pedagogical sequence using the Human Orrery on the reasoning students follow when dealing with the targeted concepts of physics.

## Methodology and Learners’ Populations

It seems unfair to ask the open questions proposed above as pre and post-tests. I was not willing to have learners looking for the answer during the sequence. If questions were given in advance or in a pre-test, the correct answer may be looked after during the sequence as defined below, as well as in the course of a comprehensive lecture on dynamics. It seemed best to let the students discover the sequence or follow a lecture without any a-priori, and ask those questions afterwards. I compared then different populations with different age and using experimental and demonstration classes, as summarized in the table 1 below. The demonstration classes are defined by classes that did not use the Orrery, but did take at least one lecture about our “targeted concepts”. Characteristics of each class are summarized in Table 1, and detailed in the SEM. Mme Richard (Lycée Condorcet) had participated to teacher training sessions that I organize regularly. She knew how to use the Orrery, but did not take part in the sequences with the Orrery, that I conducted alone for all experimental classes. Mme Cantet (Lycée Jeanne Albert in Versailles, near Paris) knew my work through the same training sessions and accepted to ask her 31 KS4 pupils to answer the same questionnaire.

**Table 1.**
***Description of classes that participated to this study, either as experimental (pupils followed the enacted sequence) or as demonstration (pupils did not use the Human Orrery but followed a class on the targeted concepts)***

| | Name of the institution | Level | Age | Number |
|---|---|---|---|---|
| Experimental classes | “Lycée” Condorcet | KS4 | 15-16 | 52 |
| | Total | | | 52 |
| Demonstration classes | “Lycée” Condorcet | KS4 | 15-16 | 17 |
| | “Lycée” Jeanne Albret | KS4 | 15-16 | 31 |
| | UPMC | L1(1) | 18-19 | 47 |
| | Master of Education | Pre-teachers | 22-23 | 37 |
| | Total | | | 132 |

**(1) 1st year undergraduate students**

I emphasize here the fact that the correct scientific answer has been taught in schools to all pupils who answered our questionnaire. All KS4 pupils are expected to be fully aware of the relation between velocity, distance and duration, that they have learned two years before. They know about gravity as the action of one mass towards another, and know its direction and evolution with the distance. KS4 demonstration classes have learned the law of inertia and had a lecture on gravity just before the questionnaire, while experimental classes discovered both during the sequence on the Orrery. So the second question is probably above the average curricula of a KS4 pupil.

First year demonstration group of University students (L1) in this study are expected to have learned and used relation (1) since at least 5 years, as well as gravity and Newton laws since about one to three years. They also followed a one semester lecture about Newtonian mechanics.

As for master degree students, they would obviously know the correct answer if they had to prepare a lecture about it. Yet, I intentionally asked them to answer at the very beginning of my lecture without any warning, and they had about fifteen minutes only to answer both questions. Other groups answered the question on-line (demonstration classes) or on papers (experimental KS4 classes) within about 20 minutes.During the first year, additional questions related to the understanding of the sequence were asked. I also use interviews made in the course of a project done within Sorbonne University.

KS4 Experimental classes, L1 and pre-teachers answered the questionnaires on paper while KS4 demonstration ones did on-line. In the “lycée Condorcet”, on-line questions were answered in the school with the supervision of the teacher. Answers were of similar length, on-line or on paper. Thus, I assume that the difference on-line vs on paper did not create bias.

## An Enacted Sequence on The Solar System

The full description of the sequence may be found in the Supplementary Electronic Material (SEM). I only summarize here the elements of the sequence required to follow the evaluation of the answers and the way notions were enacted. Readers are highly encouraged to go through the SEM to have a better understanding of what has been done with the Human Orrery.

The sequence lasts 1h30 and was conducted in three phases. It starts with an introduction (S1) to the objects present in the Orrery. This creates a short discussion about stars, comets, planets, and general knowledge in astronomy.

**Orbits of the Planets (S2)**

We then focus on the orbit of Earth (S2a). One student walks along the orbit with a constant pace. We derive the time laps of 16 days between two points (there are 23 points for Earth). The duration for the pupils may vary according to its speed, while the duration for Earth does not vary. Hence the notion of temporal scale is introduced. Before going to other planets and motions, we discuss about circular motion first (S2b). Pupils are set up in two circles and rotate around the same center. We wonder which circle will finish his turn first. This depends on their relative speed. The outer circle may finish first if it goes faster. The double influence of velocity and distance on duration is thus enacted. We then focus on Inertia (S2c), to show that the trajectory depends on the initial velocity and on the strength of the attraction (another double dependence). This is applied to orbits of Mercury and Jupiter (S2d), the bodies that are closest to the Sun and furthest from the Sun on the Human Orrery.  To reduce the speed of Jupiter, the duration between two consecutive points is of 80 days (or five steps). To increase the speed of Mercury, it goes two points at every step. The case of comets (S2d) is special since their speed is varying during their orbit (due to a large eccentricity).  We discuss the fact that points are getting closer when the comet is farther from the Sun and proceed on the different rules (see SEM for details).

**Observations: The Scientific Methodology (S3)**

As the rules for each object are clear, the choreography is repeated three times. By groups of three, pupils will play one object (the actor), check the movement of the actor or keep track of time. Thus, they are all actor or spectator, and we get three measures of period. The sequence ends by the measurement of major axis for all orbits. One week later, in the classroom, those measurements will be used to infer the Kepler law.

### Evaluation

The questions I asked in this work correspond to a “closed question” (see discussion in Frappart et al. 2014) since I asked for an explanation of a scientific fact, clearly stated. The absolute quality of answers to questionnaires is uneasy to determine since it is impossible to affirm that the absence of reference to a given concept means that the learner doesn’t know about it or that he simply did not mention it. Additional interview would be required to investigate further those questions. In the context of the research presented here, my focus was more on the impact of an enacted pedagogy. As such, comparison of answers is more useful than an assessment of their intrinsic quality.

I now discuss whether the sequence was clear enough and how it was perceived and appreciated by the learners. Then, I describe specific “elements of answer” that will quantify the agreement between answers from the different classes and the correct scientific answer. This allows for a quantitative analysis of the quality of the reasoning and, more important, of the impact of the enacted sequence.

## How Did The Pupils Understand The Sequence And How Did They Feel?

In 2015, I asked additional questions to ensure that the sequence was easy to follow, and to get an idea about their feeling during this experience. Those questions were answered by 35 KS4 pupils from the “Lycée Condorcet”.

They first had to rate their specific feeling as they enter the room and saw the Orrery on a scale going from “Curious” to “Surprised” and then “Indifferent”. 7 were “Curious”, 4 were “Surprised”, 24 were both, and none were “Indifferent”. The size of the Orrery comes out often as they comment their answer.

Their global feeling during the sequence was asked as an open question. For one group, we did the sequence outside with a quite low temperature, and with other fellows looking at us. This yields to a bad feeling for most.  Yet, the general feeling was happiness and interest. Then, they were asked if they had the feeling to have “learn in a unique way”, “participate to an unusual and interesting sequence”, “enjoy themselves” or “wasted their time”. None had the feeling to have wasted their time! The interesting point is that only 6 out of 35 pupils did not feel they had learnt something. Comments actually showed their surprise that so much may be learnt with this tool. 19 over 35 felt to have learnt with an interesting, unusual and funny sequence!

The last questions were about instructions given (1) to explain the movement, (2) to do the “choreography”, and (3) to obtain the measurements. The questions started with: “Did you feel that you understood what you had to do...”. It was not about their understanding of the concepts, but of the instructions only. A large majority (28, 33, 25 for steps 1-2-3 respectively) had no difficulties to follow the instructions. Only 1, 0 and 2 pupils respectively could not follow those instructions.

It was clear then that the sequence was easy enough to follow by KS4 pupils, and that it was more appealing to them as compared to a lecture in a classroom. According to teachers, the atmosphere in the KS4 classes, and in other KS3 classes in Paris (not included in this paper), was better after the activity.

To support this observation, I mention here the results of a former project, made at the early stage of the development of the Orrery. Together with colleagues of Paris Sorbonne (Paris IV) and UPMC (Paris VI), I set up a series of three workshops with university students. One of them was with the Orrery and Italian theatre; another on Ancient Greek and astronomy (music, rhythm of ancient Greek poetry and science); the third one was on biology and dance. I conducted individual interviews with the students afterwards that confirm the positive impact of multidisciplinary and of enaction. The results of this project were published in a French Colloquium (Rollinde et al. 2015, in french). I translate here the most meaningful sentences related to enaction and interaction. They are all consistent with the feedbacks from teachers and learners involved in the practice of the Orrery:

> “The workshops have allowed the students to renew with the joy of inter-personal contacts. One student who looked afterwards at the video of the workshop on the Orrery reacts spontaneously with the words: ‘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.’ The formal knowledge of planets trajectories is reinforced as they are shown, enacted by the learners.
>
> Another student suggested that ‘illustrating a concept with a movement makes it more real. We feel that we live it’. Yet, our goal is to go deeper than an illustration, up to the embodiment of the concept that engages both body and mind.”

In forthcoming projects, we shall use the tests developed by F. Fenouillet and his colleagues (Besançon, Fenouillet, & Shankland, 2015; Fenouillet, Heutte, Martin-Krumm, & Boniwell, 2015) to investigate the well-being of learners during such enacted sequence, and the correlation with their motivation in learning.

## Scientific Answers

For each question, I define here “elements of answer” that I look after in each individual answer to determine to which extent they may be considered as consistent with the scientific model. Those elements are related to different parts of the enacted sequence or to pre-requisite knowledge, as described in the Table 2.

**Q1: ‘Explain why Jupiter takes more time than Earth to go around the Sun.’** The scientific answer may be phrased as: "The period of Jupiter and Earth are linked to the length of their orbit and to their velocity. On the one hand, the length of Jupiter's orbit is larger than the Earth's one. On the other hand, due to the fact that Jupiter encounters a smaller gravitational attraction per kg by the Sun than Earth, its velocity has to be smaller. Both factors act towards a larger period for Jupiter."

**Table 2.**
***Presence of different elements of the scientific answer for the two questions (Q1 and Q2) in the enacted sequence***

| | Elements of the scientific answer | Related enacted sequence |
|---|---|---|
| General | Time and space | Scales (S2a) |
| Q1 | Velocity, duration and length of a path | Circles (S2b) and Jupiter (S2d) |
| | Strength of the force / Distance to the Sun | Pre-requisite knowledge |
| | Velocity / Distance to the Sun | Choreography (S2-S3) |
| Q1 and Q2 | Force / Trajectory | Comets (S2e) |
| Q2 | Initial velocity / Trajectory | Inertia (S2c) and Jupiter (S2d) |
| | Gravity vs weight | Pre-requisite knowledge |

An answer is considered as fully consistent if it contains the elements "length of the orbit" or "distance to the Sun", "velocity" and “gravity”. The two first elements express the different length of the orbits.  I assumed that if someone writes that Jupiter is further away, he expresses the fact that it has a larger orbit even if it is not explicit. The third one expresses the double influence of distance and velocity on the period. The last one hints toward an explanation of the smaller velocity of Jupiter.

Therefore, I define three types of answers by increasing consistency with the scientific one: “V” (includes velocity), “V+D” (includes velocity and distance), “V+D+G” (includes gravity also).

A reference to the length of the orbit only is already a correct answer in the context of the Solar System. Yet, the knowledge I am looking for is that notions of duration (or period) must be related to two variables (velocity and distance). Thus, in the analysis below, I consider that an explanation based solely on the distance is incorrect.

More specifically, if there is an explicit reference to the laws of Kepler (for example, "this has been observed by Kepler") I consider this answer either as correct or incorrect in the analysis.

It happens only for 6 L1 students (over 47), but for 6 pre-teachers over 19 in 2016. I explicitly told the pre-teachers not to use Kepler as a justification in 2017.

**Q2: 'Explain why an apple falls on the surface of the Earth while the Moon orbits around the Earth'.** The correct answer may be phrased as: "Both apple and Moon are subjected to the force of gravity, directed towards the center of Earth. Yet, the apple is left initially with a zero velocity (relative to the ground) while the Moon has a large tangential initial velocity (relative to Earth). Both objects are attracted towards the ground or the Earth, but the initial velocity of the Moon makes it turn constantly around Earth."

A correct answer must then contain the words "velocity" and "gravity". Ideally, we should expect a mention of the referential frame or at least of what is the velocity relative to. Yet, the notion of referential frame is complex and would require a specific attention which was done neither in our enacted sequence nor in the lectures in classroom.

Again, I define two types of answers by increasing consistency with the scientific one: "V" (includes initial velocity or velocity only), "V+A" (includes a competition between attraction and velocity). A mention to "inertia" (I) or to a counterbalance between inertia and gravity is looked for since it would express a deeper understanding of the physics.

The issue of referential frame in the phrasing of the question (mentioned in the section Overview of the Research) did not appear in any of the answers, but in five: one pre-teacher and four L1 students. Among them, the pre-teacher refers to distance as an explanation for the different trajectories, while L1 students refer to difference between the two forces that act on the apple and on the Moon (either the nature of the force or the strength of the force). None of them refer to a difference in initial velocity, nor do they refer to inertia. I will not consider those specific cases afterwards, and I consider then that all learners understood both situations, albeit not necessarily the underlying difference of reference frames.

## Quantitative Analysis of the Answers

Tables 3 and 4 provide the number of correct (True) and False answers for the two open questions, according to the types of answers defined above, and for the different groups considered in this study.

**Table 3.**
***Number of True/False answers to question 1, for different groups*.**

| | | Question 1 : Periods of Jupiter and Earth | | | | | |
|---|---|---|---|---|---|---|---|
| | | G+V+D | | V+D | | V | |
| | TTotal | T | F | T | F | T | F |
| KS4 (experimental) | 52 | 3 | 49 | 13 | 39 | 22 | 30 |
| KS4 (demonstration) | 48 | 0 | 48 | 2 | 46 | 2 | 46 |
| L1 (demonstration) | 47 | 0 (6) | 47 (41) | 9 (15) | 38 (32) | 14 (20) | 33 (27) |
| Pre-teachers (demonstration) | 37 | 1 (7) | 36 (30) | 10 (16) | 27 (21) | 12 (18) | 25 (19) |
| All experimental | 52 | 3 | 49 | 13 | 39 | 22 | 30 |
| All demonstration | 132 | 1 (13) | 131 (119) | 21 (33) | 111 (99) | 28 (40) | 104 (92) |

***Note:* Letters hold for different criteria of correctness: Gravity, Velocity and Distance. Numbers under bracket consider the reference to Kepler laws as a True answer. Pairs of cells are colored according to the Fisher test's probability within four ranges (from dark to light): 0-0.01; 0.01-0.05; 0.05-0.1; above 0.1**

Some comments about question 1: (i) numbers in the table assume that an answer that uses Kepler relation as a proof is false. Numbers under bracket consider it as True. This impacts only L1 (demonstration) and pre-teachers. (ii) All type of correct answers considered here include a reference to velocity. This assumed that being aware of the influence of the length of the orbit is "trivial". This is confirmed by the fact that all answers did include a reference to either the length of the orbit or to the distance to the Sun (which in turn relates to the length of the orbit). Only 4 KS4 pupils described solely a difference in mass to explain the different period.

**Table 4.**
***Number of True/False answers to question 2, for different groups*. (Same as Table 3)**

| | Question 2 : Apple and Moon |
|---|---|

| | | V+A | | V | | Inertia | |
|---|---|---|---|---|---|---|---|
| | Total | T | F | T | F | T | F |
| KS4 (experimental) | 52 | 13 | 39 | 20 | 32 | 4 | 48 |
| KS4 (demonstration) | 48 | 5 | 43 | 20 | 28 | 0 | 48 |
| L1 (demonstration) | 47 | 9 | 38 | 12 | 35 | 0 | 47 |
| Pre-teachers | 37 | 5 | 32 | 16 | 21 | 0 | 37 |
| All Experimental | 52 | 13 | 39 | 20 | 32 | 4 | 48 |
| All demonstration | 132 | 19 | 113 | 48 | 84 | 0 | 132 |

To estimate the impact of the enacted sequence, I applied a Fisher Test(2) to compare experimental and demonstration groups. I did it for the two KS4 groups (two first lines) and for the two groups considered as a whole (two last lines). Cells are highlighted in light grey when the null hypothesis (of equal distribution) has a probability below 0.1, in grey when it is below 0.05 and in dark grey when it is below 0.01 (for question 1, the color corresponds to a test done assuming that “Kepler” is not a correct answer).

I also applied such a comparison between the two “demonstration KS4 classes” (from the Lycée Condorcet and Jeanne Albert). They show no statistical difference and are thus considered as one group in this analysis.

**Global quality of the answers**. The most striking fact when looking at the results of the analysis as a whole is that the knowledge about the “targeted concepts” of physics is globally low, since no group has a majority of correct answer even for the simplest criteria. Globally, answers to question 2 are better than to question 1.  The reference to attraction or gravity is more often noted for the second question than for the first one, which is not surprising. Yet, nobody refers to inertia (except 4 KS4 pupils in the experimental class).

It is interesting next to search for an evolution with the age of the learner, by considering only demonstration groups. The understanding that velocity has to be considered when discussing a period (question 1) is much better for L1 students and at a similar level for pre-teachers. Yet, the link with gravity stays at a very low level at all ages. The second question shows little or no evolution with age. This may be surprising since question 1 corresponds to a curriculum below KS4, while question 2 is slightly above.

These observations point towards the idea that the "targeted concepts" are indeed a relevant challenge for science education. I will now show that the enacted sequence is a promising way to make those concepts better understood by pupils.

**Impact of the enacted sequence.** In all cases, experimental classes do better or similar score as compared to demonstration classes of the same age. The issue encountered with Kepler relations make the comparison less easy, but it never shifts this comparison in favour of the demonstration classes versus experimental ones (considering the same level). Assuming that a reference to Kepler is a "False Answer" would make the score of KS4 experimental classes even better then pre-teachers in all cases, but (V+D, question 1) and (V, question 2).

The reference to a velocity difference only (V) is done more often for KS4 experimental vs KS4 demonstration classes with a probability of similar distribution of p=4e-6, and for all experimental vs all demonstration classes with p=0,005. A clear reference to both velocity and distance is statistically more present for KS4 experimental classes compared to demonstration one (p=0,004). The correct answer (G+V+D) is proposed by only a few KS4 pupils in experimental classes. The numbers are not large enough to be significant when comparing with KS4 classes only. Considering all demonstration classes, and rejecting a reference to Kepler relations, creates a difference that corresponds to p=0.07. Relation (1) and the question of time and space were often present in the enacted sequence (see Table 2). Besides, perception of speed is easier to enact than perception of forces, as will be revealed by the second question.

Question 2 was indeed a more complex question, for which a correct answer should contain many different keywords. Enaction of forces was less present in the sequence. Thus, a correct answer required more pre-requisite than the first question. It is amazing to note that our KS4 classes obtain a better score than 1st year university students or even pre-teachers when considering references to velocity and attraction. Although the experimental classes are doing better compared to the similar demonstration classes in all cases but (V), the significance is less than for question 1 (table 3). Note that the better score of KS4 demonstration vs KS4 experimental for (V) corresponds to a Fisher Test of 0.8.

Finally, the reference to the inertial principle (or at least to the word or to a rectilinear movement in the absence of interaction) appears only in the KS4 experimental class! Even though the numbers are low, the result of the Fisher test for experimental vs demonstration classes is p=0.006 considering all groups.

I consider those results as encouraging for the future. There are indeed clear trends towards a positive impact of the proposed sequence on the understanding of the concepts of physics considered in this work. Going further requires different improvements in the method of evaluation, in the groups of pupils considered, and in the sequence itself. Those are discussed in the conclusion.

## Conclusion and Perspectives

For three years, I have had the pleasure to work with KS4 pupils in Paris making them enact our Solar System. My personal feeling and those of the teachers associated with this work was that learners had more pleasure and were more eager to learn as their body is involved. This is in agreement with the claim of enacted theorists that “cognition is action”. The questionnaires and interviews made in the course of this work are a clear but still qualitative and quite general confirmation of this link.

Is the pleasure of learning in relation with its quality? Compared to other studies about embodied pedagogy, the one I propose here is for the first time (to my knowledge) done in real conditions of learning with a class (inside the school and in a limited time), and with a class old enough to deal with abstract and complex scientific notions (compared to elementary classes). This work is centered on the solar system, and on knowledge about velocity, trajectories and gravitational force. It is hence based on a well-defined sequence and associated questions. The population I worked with was still limited. The presence of classes with higher level was useful in this work to confirm the persistence of conceptions about velocity and forces, but is not necessary for future analysis. The quantitative results obtained through two open questions are very promising about the potential impact of embodied pedagogy. For additional discussion about a specific link between embodied cognition and difficulties in reasoning see the second section of the Supplementary Electronic Material.

One major challenge in the future will be to better describe and measure the embodiment of learners during the sequence. According to Johnson-Glenberg et al. (2016) taxonomy, for content to be considered minimally embodied it should contain three constructs: (a) sensorimotoric engagement, (b) gestural congruency, that is, how well-mapped the evoked gesture is to the content to be learned (see Segal, 2011), and (c) evoke a sense of immersion. The results of this work and the mentioned interviews have shown that the first construct is already at least partially present. Actions in the Orrery are clearly congruent. Although not "gestures" of the usual sort, the actions are congruent with the concepts the students are meant to learn. For example, time and space during the enacted sequence is directly correlated with time and space in the Solar System. The concept of velocity is then congruent. I believe that the notions of force and inertia may still be better "gestured" in future sequences. We need to define in a more detailed way the link between gesture and science concepts when walking along the Human Orrery, in line with the representational approach (Sutopo & Waldrip, 2014).

About immersion, Coomans and Timmermans (1997) state that immersion is "...the feeling of being deeply engaged... (in) a make believe world as if it was real." (p. 279). Immersion is subjective, difficult to precisely quantify, and results have been mixed on its effects on learning. Immersion concept is probably linked somehow with the feeling of well-being that the learners will encounter during the sequence. If deeply immersed, he should not be disturbed by the outer events, and he should feel more comfortable. While walking on the Human Orrery, students are at least partially immersed. Although they may not believe that they are literally acting in the solar system (as may be the case in virtual environments), they are certainly acting in the Orrery rather than just reading about it or even just watching others act. Also, they must closely attend to components such as claps.

I suggest here possible lines of improvement for the future. The sequence itself may include more counterintuitive situations to help cognitive conflicts to arise (Lee & Yi, 2013; Balta & Eryýlmaz, 2017). The pedagogical impact may also be improved using complementary approaches to the embodied one, such as representational approach (see Sutopo & Waldrip, 2014 and references therein) the gestures being only one of the possible representations, or the deductive reasoning (Lee & Park, 2013).

The results obtained with this work are in line with the claim that "cognition is action". They show that cognition is facilitated when actions are consistent with abstract concepts, and when students' body are considered as much as their mind. This is a clear motivation to continue using the Human Orrery in the classroom. Ongoing research projects, after this initial work and its promising results, will look more closely after a quantitative proof of an impact of the Human Orrery on student's content knowledge performance (with a constant focus on physics concepts rather than astronomical knowledge) and on their motivation and well-being.

**Notes**

(1) NASA web site: https://kepler.nasa.gov/multimedia/animations/orrery3/, or the Astronomical Society of the Pacific, http://www.astrosociety.org/wp-content/uploads/2013/02/uitc82.pdf

Web site of the project http://planetaire.over-blog.com and http://euhou.net

(2) The Fisher's Exact Test were computed with the software R, using the p-value returned by the routine "fisher.test"

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**Supplementary Electronic Materiels (SEM)**

## Astronomy in The Classroom

Due to an increasing proportion of astronomy being taught at all levels, science education researchers are now devoting considerable attention to this specialized field of teaching and learning that is called astronomy education research.

The interest of science education researchers for astronomy may be related to the fact that the context of Universe helps to show alternative conceptions that cannot be justified within a terrestrial context. Among many, we can cite the movement related to different referential frame, the absence of friction, the notion of verticality, the issue of mass versus weight and gravity… Pre-conceptions in astronomy are especially prominent as this is an area where most students have no previous experience. Despite this possibility, Bailey and Slater (2005) found in their review of studies within astronomy education that most of the students' preconceptions considered in those works include e.g. the cause of seasons, lunar phases, and the day-night cycle, but no conceptions related to general physics concepts, such as those studied in e.g. Hestenes et al. (1992) or Treagust & Duit (2008). Similarly, Lelliott and Rollnick (2010) review astronomy education research carried out among school students, teachers, and museum visitors over a 35-year period from 1974 until 2008. One hundred and three peer-reviewed journal articles were examined, the majority of whose research dealt with conceptions of astronomical phenomena with 40% investigating intervention activities. 80% of the studies were concerned with conceptions of the Earth, gravity, the day–night cycle, the seasons, and the Earth–Sun–Moon system. Most of the remaining studies were of stars, the solar system, and the concepts of size and distance. Astronomy is often used as a way to engage the students in their activities through inquiry-based interventions (e.g. The Faulkes Telescope Project described in Beare et al. 2007, the lifecycle of stars in Fitzgerald et al. 2015, or the use of planetarium in Persson & Eriksson, 2016) which may tend to elude the basic scientific contents in favor of fashionable scientific subjects. The case of the Faulkes Telescope as reported in Beare et al is very interesting. It is very much appreciated by students, who found it interesting, challenging and rewarding. Yet, their score on previous science courses is highly correlated with their mark for the project, while their enthusiasm is not correlated with their mark. As stated by Beare et al, those who were more able were not markedly more enthusiastic about the project. The results obtained by Fitzgerald et al support this observation and also enhance the needs for teacher training in order to have students engage in real scientific discussion. To, using astronomy does help to motivate students in the classroom, but is not sufficient to improve their learning of science.

I 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. The work done by Plummer et al (2011, 2014) on "learning to explain astronomy across moving frames of reference" is exemplary in that regard. From a broader standpoint, Nilsen & Angell (2014) discuss the factors that explain why Norwegian 8th graders are successful in the TIMSS sub-topic of astronomy, in contradiction with the general students' disenchantment with what are referred to as the STEM-subjects, i.e. science, technology, engineering and mathematics (an increasing concern in education policy and practice since the mid 1990's). Nilsen & Angel emphasize the importance of language and attitude in the learning of science. Then, the core process of astronomy, namely mental model building, should be reflected in astronomy education (see Taylor, Baker and Jones 2003). This crucial skill may promote a better understanding of the nature of science by pupils.

# Description of Learners' Population

**Table 5.**
***Description of classes that participated to this study, either as experimental (pupils followed the enacted sequence) or as demonstration (pupils did not use the Human Orrery but followed a class on the targeted concepts)***

| | Name of the institution | Level | Age | Number |
|---|---|---|---|---|
| Experimental classes | "Lycée" Condorcet | KS4 | 15-16 | 52 |
| | Total | | | 52 |
| Demonstration classes | "Lycée" Condorcet | KS4 | 15-16 | 17 |
| | "Lycée" Jeanne Albret | KS4 | 15-16 | 31 |
| | UPMC | L1 | 18-19 | 47 |
| | Master of Education | Pre-teachers | 22-23 | 37 |
| | Total | | | 132 |

**(1) 1st year undergraduate students**

*Experimental classes.* The main focus was on 15 years old pupils, in the class of "Seconde" (French system) that corresponds to KS4 in UK or 9th-10th stage in USA. In 2015 and 2016, I was invited by Mme Richard, science teacher, to conduct sequences with her class in the "Lycée Condorcet". Mme Richard had participated to teacher training sessions that I organize regularly. She was aware of the way one may use the Orrery, but she did not take part in the sequences with the Orrery. This school is considered as a very good school in Paris. The class was split in two groups, with about 15 pupils each. In total, 52 pupils answered the questionnaire one week after the sequence, and before any specific lecture linked to our "targeted concepts".

This group is the experimental class (52 learners).

*Demonstration classes.* Mme Richard had another KS4 class to whom she taught our "targeted concepts". 17 pupils of this class answered the questionnaire after her lecture, in January 2017. Mme Cantet, a teacher from the "lycée" Jeanne Albert in Versailles (near Paris) who knew my work through the same training sessions, accepted to ask her 31 KS4 pupils to answer the same questionnaire. The total "demonstration KS4 pupils" is of 48, close to the "experimental" ones.

I also teach the physics class "Concept and Methods of Physics" in the first semester at the University UPMC. The group I had in charge is composed of voluntary students who need additional support (smaller groups and additional time for lectures). They are selected according to their results at the "baccalauréat" (bachelor's degree) so that they correspond to a medium (quite low) level in mathematics and in physics. Yet, they passed their bachelor's degree, and followed one semester of physics, so it is reasonable to assume that they should have a similar or higher knowledge of physics as compared to KS4 pupils. 22 students of this class answered the questionnaire at the end of the first semester in December 2016 (they were 30 at the beginning of the semester).

I teach another class during the second semester whose students followed the same lecture "Concept and Methods of Physics" during the first semester, but with another teacher. They are "standard" students whose main subject is computing rather than physics. I had thus 25 more students answering the questionnaire in January 2017, at the beginning of the second semester. This accounts to a total of 47 "L1 students".

Lastly, in 2016 and 2017, I taught a lecture on "embodied physics teaching" for pre-teachers in Paris. They all took curricula in Science up to the master level, and passed the exam to become a science teacher in secondary schools. I have them answering the two questions right as they enter the classroom. They were 19 in 2016 and 18 in 2017.

Those three groups (KS4, L1 and pre-teachers: 132 learners) are the demonstration classes.

## An Enacted Sequence on the Solar System

The sequences were all conducted with a similar structure: introduction to the bodies in the Solar System; description and practice of the movements of the planets and comets together with a special interest in inertia; and measurements of period and distance. I have done this activity for about three years. Over time, some improvements have been made. Yet, the scientific contents and structure have remained identical.

The sequence on the Orrery lasts one hour and half, while the analysis of measurements is done one week later usually.

**Introduction (S1)**

Students are put in motion right away as they are requested to install the Orrery made of three 12 meters long bands (Figure 2)! Once settled, we all join around the Asteroid Bell, and I make them name the objects represented on the Orrery.  Here are some remarks that I collected during this introductory phase about general education in astronomy. They are of interest for other studies that would focus on astronomy and not on physics.

> The distinction between a star and a planet is obvious for most. I have the impression that all knew stars are not in the Solar System, which seems less obvious with younger pupils. Yet, this has to be further confirmed.
>
> A majority knows the name and order of the planets. Yet, the existence of the asteroid belt is not as clear, and the name of the "planet with rings" is not always known.
>
> Distances and sizes are not obvious for all. Many pupils are searching for the moon, which is so close to the Earth that it would be located behind its circle. Although many are aware of the Astronomical Units (that is introduced in previous classes), some may propose the light-year as a typical distance for Solar System. Those who propose it are aware that light-year is indeed a distance.
>
> In 2015, all knew about the comet Churyumov-Gerasimenko that was visited in 2014 by Rosetta, a European Space mission. In 2017, it is known by a few only.

*Figure 2.* **Introduction. Pupils install the Human Orrery (left) and describe the Solar System (right)**

## Orbits of the Planets: Velocity, Distance, Duration (S2)

**Orbit of Earth (S2a).** The sequence continues with an emphasis on Earth (Figure 3, left). Its orbit is split into 23 steps. While one pupil walks along the orbit, others have to guess the duration for one step. We expect them to propose half a week, while the exact duration is 16 days.

They then clap and the Earth-pupil follows the rythm. Clapping faster increases the tempo and thus decreases the duration of one year on the Orrery. Through this simple act, the notion of temporal scale is introduced. They do not realize that the tempo is a temporal scale, while they rapidly find out that the distance between Earth and Sun is a spatial scale. It is interesting to note that temporal scale is less intuitive to them than spatial scale. This difficulty will appear again while they measure periods.

*Figure 3.* **Description of orbits. Orbits of Earth, Jupiter and the Comet Encke (left) together with circular motions (right) are used to illustrate the velocity-distance-duration relation**

**Circular motions (S2b).** In order to discuss velocities, pupils are set in circles with different radius (Figure 3, right). As they rotate around the centre (the Sun), I ask the definition of period, linear velocity and radial velocity. And I ask which circle is going to end its turn first. The "obvious" answer is the inner one. Yet, to justify it, they refer to the smaller length of the perimeter. I then ask if it must always be the case that the inner one has the shortest period. Some pupils will start talking about velocities, but a minority only. Thus, I make the inner circle go very slowly and the outer one go very fast, without warning the other one. The conclusion is clear: the period depends on the velocity too!

If time allows, it is nice to go further on this question. Pupils are then set in a cross, with four arms. They are then asked to walk with arms always aligned and in right angles. This makes a solid body rotation, with a constant angular speed. One may then discuss about the evolution of linear velocity and angular velocity with distance to the center.

We then proceed to the orbits of Earth and Jupiter. One pupil makes the Earth, another one Jupiter. They both start walking as they wish. They will naturally walk at about the same pace, and Jupiter's period is then longer. If required, it is possible to insist and ask that Jupiter finishes his rotation before the Earth. This makes funny memories when Jupiter has to run very fast. Such stories will spring to mind more easily than equations! I now ask pupils what should do the "real" Jupiter, which comes to the question of inertia...

**Inertia (S2c).** The concept of inertia is counter-intuitive due to the continuous presence of friction in our everyday life. I have tried different ways to make pupils feel it through their own perception. The use of virtual reality is a great help for such a goal (such as the Meteor project in Lindgren & Moshell, 2011), but it is uneasy to use in standard educational context. Using 'enacted inertia', I insist first on the existence of friction and interaction.

I make pupils walk along the Orrery (used as a floor mat) in straight lines. I then ask them to turn at some random points, and ask them how did they turn. They usually get quite confused and talk about their brain, mind, muscles… I guide them to think more about their sensation rather than their consciousness. We then end up by an understanding that a change of direction requires an interaction with the floor. It is now easier to proceed into the movement of a planet that interacts only with the Sun.

I take one pupil to be the planet. He must first admit that he will not move at all if there is no other material objects around him… Then, I ask a pupil to be the Sun. I propose to see him (her) as a very attractive person (another unforgettable moment). I hold the planet for a moment and then leave it to the single interaction with the Sun. At first, some pupils will start a circular orbit around the Sun. After discussion, it appears that this requires an interaction with the floor that does not exist for the planet. Then, the planet-pupil goes straight to the Sun. According to the global level of the class, I will propose or not that it should accelerate all the way to the Sun. Now, I may push a little bit the pupil-planet and let him do his own trajectory; then push harder and harder until he (she) accepts to go straight. Most pupils will end up with a circular motion before long. But eventually, if I push hard, or through others' reactions, they accept to leave the scene without orbiting around the Sun. The conclusion of the discussion must be: "To escape the attraction of the Sun, the planet must have a strong enough initial velocity".

**Mercury and Jupiter's orbits (S2d).** While Earth is still rotating with its own pace, we now have to finalize Jupiter's orbit. It is straightforward to notice that points along its orbit are separated by a larger distance than along the Earth's orbit. So, if Jupiter-pupil makes one step every clap, and goes into the next point after every step, he will go faster than Earth (the duration between two claps is fixed to 16 terrestrial days). Doing so, the class discusses the decrease of gravitational force with distance. They conclude that the speed of Jupiter must be lower, otherwise it will escape from Sun's attraction. After discussing again about the link between velocity, space and distance, it is clear that Jupiter has to make several steps before reaching the next point. Yet, I have to state the correct rule for Jupiter's pace, in order to obtain the right velocity: "Jupiter makes one step every clap, the duration between two claps is still 16 terrestrial days; the distance from one point to the next is covered in five steps. The travel time between two points is thus 80 terrestrial days."

One proceeds then to Mercury, the closest planet to the Sun. Here, pupils often propose directly that Mercury has to go very fast otherwise it will fall into the Sun. I always let the discussion continue among pupils until all agree with this statement, and then state the rule: "Mercury makes one step every clap, but goes every two points at each step. The duration between every two consecutive points is thus 16 terrestrial days. During each orbit, Mercury goes into half of the points located along the orbit."

Mars and Venus movements are similar to Earth's. They make one step every clap, and reach the next point every step. The duration between two points is 16 terrestrial days. Pupils may already be aware, if they are concentrated enough, that the velocity decreases with distance to the Sun.

**Comets: force and velocity (S2e).** The next step is the understanding of comet's orbits. Due to their large eccentricity, the distance to the Sun varies. While walking along Encke's orbit, the pupil will find out that points are getting closer as it moves away from the Sun and all conclude that it decelerates. As I ask the reason for this modification of the velocity, some pupils will compare again the distance between two consecutive points, which is fine and true. I then ask the physical reason for it. They quite often make a link between the distance to the Sun, or the strength of the force, and the variation of velocity: 'the velocity decreases because the comet is further away (or because the force is small)'. Yet, an analysis of two symmetrical points located at the same distance to the Sun, but while the comet is moving away or towards the Sun shows that there is no direct relation between distance and velocity changes. The main issue, already known in the study of velocity-distance graphs (*e.g.* Goldberg & Anderson 1989, and analysis of the Test of Understanding Graphs by Beichner (1994), is that pupils consider only the absolute value of the velocity, and do not consider its relative value, and even less its direction.

We end up with the rules for all orbits: 'Everyone makes one step every clap; the comet Encke waits three steps to reach the next point, even if it is very close! Earth, Venus and Mars reach the next point every step. The comet Churyumov and the asteroid Ceres waits five steps to reach the next point, as for Jupiter. Mercury walks one in two points every step."

**Observations: the Scientific Methodology (S3)**

Once the movement of all planets and comets are clear for all pupils, we set up about five to six groups of three (this is close to the average number of pupils in one class). Each group is coupled with one body in the Orrery.  Missing bodies will be studied afterwards in the class by extrapolation or interpolation. I explain to them that our goal, as scientist, is now to observe and describe the movement of celestial bodies: is it erratic or governed by some relations? The first step is to uncover any hidden consistency. To do so, one wonders which quantities may be measured. The notion of time and distance are usually proposed by pupils. I propose to start with time measurement and I clarify the correct name that is "period".

**Measure of period (S3a).** We shall do three times the full choreography in order to get three measures of the period. In each group, one pupil will do the planet, and follow its pace according to the rules. The second pupil will check if the pace is correct, and will announce when one orbit is completed. The third one is in charge of the stopwatch, and write down the time (Figure 4). At each round, roles are exchanged.

***Figure 4*. Pupils walk on the Orrery to estimate the period of planets and comets**

The planets, comets and asteroid keep turning until the comet Encke ends one orbit. Thus, inner planets will do more than one orbit; the asteroid Cérès, the comet Churyumov and Jupiter will not finish one turn (their period is larger than Encke’s one). Inner planets may then estimate an uncertainty using multiple measures. Others have to prorate the last points reached to account for the total number of points along the orbit. At the end, all periods are known, as measured during the choreography. It is always a pleasure to see the concentration of pupils during this sequence, regardless of their age.

I modify the pace for the second and third choreography, with a very slow and a very fast pace. Thus, they end up with three different estimation of the period. Although they understand why (they have walked with different pace), they find it uneasy to infer a solution to get the real period of the celestial bodies. The idea of temporal scaling using Earth measured period is not straightforward, although they agree with it as soon as a pupil, or I, propose it.

**Measure of distance (S3b).** Once the pupils have measured one parameter, that is the period, we wonder if they will be able to infer some consistencies. They naively propose sentences that link two quantities, and we thus decide that we need to measure a second quantity! They often suggest to measure masses or radius or quantities related to the physical description of the planets alone (see a more global perspective in Glenberg et al. 2013 about the importance of inner perception to explain outer phenomena). I tell them that this cannot be measured with the Orrery, and that further analysis of those parameters will be possible using data that they may collect on the web. We end up with the measure of distance.

As they suggest measuring the length of the perimeter, or the distance to the Sun, I let them try. They realize that there is no unique way to define the distance to the Sun, due to the “strange” shape of the orbit. Some classes had learned about ellipse in the class of mathematics, some not. In any case, we discuss the difference between circle and ellipse, the definition of the major axis in relation to the diameter of a circle. And we derive a practical way to derive this length, using a simple rope and a meter.

Again, all classes are concentrating and work in a collaborative way (Figure 5).

***Figure 5.*** **Pupils measure the semi-axis of different orbits**

**Summary and Extension**

During this sequence, that lasts about 1h30, different notions are discussed, observed or enacted. Most of them are related to elements of answers to the open questions (see Table 2 in the evaluation section). In a chronological order, we encounter objects in the Solar System; velocity-distance-duration relation; inertia; force and acceleration; scale (temporal and spatial); uncertainties; geometry; methodology of science.

This work continues in class. Since it is not the focus of this work, I only give indications of what has been done. Additional details may be provided on request. Pupils put in common their measures, convert them into years and astronomical units, and made a graph or a table. They found out Kepler relation between period and major axis. This relation allows them to derive period or distance for bodies that were missing in the choreography, or for further away planets not present in our Orrery.

During the process, they may discuss the (lack of) influence of physical parameters such as the mass, radius or temperature of the planets. Some classes have gone further with a work on exoplanet. They retrieved physical and observational data about exoplanets (through the web site exoplanet.eu), and found out the influence of the mass of the star on the Kepler law. They may proceed to image analysis using the EU-HOU software SalsaJ and associated exercises (see Boër et al. 2001, Doran et al. 2012 and Rollinde et al. 2016).

A further work on the Comets' orbit in the Orrery would allow learners to construct velocity and acceleration vector. Using the second law of Newton, they may derive the functional relation between the gravitational force and distance. This work is very pedagogical and may introduce the historical link used by Newton between movement of planets, Moon and an apple (as suggested e.g. in the PhD work of Maron 2015). The construction of the acceleration vectors makes also a nice application in mathematics.

In other schools, the design of the planets' orbits has been drawn by children and printed out either on a trap or on the ground. It will be used thereafter by different teachers (physics, mathematics, technology and sports) and will be the subject of forthcoming projects of research.

## Cognition and Embodiment

In this section, I introduce the "linear causal reasoning" that is known to induce errors in cases where three quantities are related, such as velocity-distance-duration. I then make a connection with a specific aspect of embodied cognition, namely the "cognition off-load" as described by Wilson (2002).

### "Linear-Causal-Reasoning"

When reasoning about velocity, accounting simultaneously for both duration and length is a well-known difficulty (Crépault, 1989; Thompson, 1994; Siegler 2006; Albert, Kirchmeier-Rust, & Matsuda, 2008). In the first question about period, it appears that a majority of pupils accounts for distance (a larger period is related to a larger distance) and do not account for velocity. Learners will progressively acknowledge the double dependence, but they will always proceed sequentially while keeping one of the three variables fixed. This has been introduced as the "linear-causal reasoning" in the doctoral works of Closset (1983) in the field of electronics and Rozier (1988) in thermodynamics. Trudel & Métioui (2011) have shown that relation (1) is well applied by learners as long as the situation considered is an idealized one, without links to a real one. The difficulty arises as soon as real objects are studied, or as the attention is focused onto the trajectories. This influence of real or idealized objects makes a connection with embodiment.

### Cognition Off-loads

Wilson (2002) explains that "we off-load cognitive work onto the environment. Because of limits on our information-processing abilities (e.g., limits on attention and working memory), we exploit the environment to reduce the cognitive workload. We make the environment hold or even manipulate information for us, and we harvest that information only on a need-to-know basis." Another aspect of the embodied cognition is that off-line cognition is body-based. "Even when decoupled from the environment, the activity of the mind is grounded in mechanisms of sensory processing and motor control. (…) In general, the function of these sensorimotor resources is to run a simulation of some aspect of the physical world, as a means of representing information or drawing inferences." The enacted sequence gives many opportunities for learners to ground their reasoning about equation (1) in their own perceptions of movements. This certainly is one of the reasons why there was a significantly larger fraction of answers by experimental classes that accounted for velocity difference between Jupiter and Earth. Additional tests (interviews and questionnaires) are required to determine if it is the only one…