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Board Games and Board Game Design as Learning Tools for Complex Scientific Concepts:
Some Experiences

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ABSTRACT

In this paper the authors report different experiences in the use of board games as learning tools for complex and abstract scientific concepts such as Quantum Mechanics, Relativity or nano-biotechnologies. In particular we describe "Quantum Race", designed for the introduction of Quantum Mechanical principles, "Lab on a chip", concerning the immune system and the nano-biotechnologies, "Time Race", created to explain Relativistic concepts such as time dilation. The main idea is to choose a core of few basic concepts to be explained, and to design the game mechanisms and rules completely around them. Each game has been played by about 1000 participants, mainly students, with excellent results concerning growth of interest and comprehension on the considered themes. In a second phase (still in progress) the authors are considering the possibility to use the direct engagement of learners in the creation of games of this kind as a learning tool for scientific subjects, in particular for light and photonics. They present in detail these activities with obtained and expected results and issues.

KEYWORDS

Board Game Design, Board Games, Nano-Biotechnologies, Quantum Mechanics, Relativity, STEM

INTRODUCTION

The understanding and learning of complex scientific concepts, for example related to modern Physics subjects, may present a series of difficulties (Perkins 1999, Meyer 2003, Perkins 2006, Perkins 2010), which are due to two main causes:

1. These concepts can appear far away from the everyday experience of learners, therefore they could result anti-intuitive and paradoxical and lead to an attitude of rejection and closure;
2. It is often difficult to find correct and non-misleading examples and analogies that can help in the explanation of such concepts in the absence of adequate cultural and mathematical prerequisites.

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This is particularly true, for example, in Quantum mechanics (with concepts such as wave-particle dualism, delocalization, collapse of the state under observation, uncertainty principle etc.) and in Relativity (proper time, time dilation, space contraction, effect of gravity on the flow of time etc).

The use of games can be particularly helpful in the understanding and learning of abstract concepts of this kind (Bright 1983, Gee 2007a, Gee 2007b, Salen 2008, Whitton 2010, Whitton 2012). In particular, board games have been tested as effective learning tools (Gobet 2004, Shanklin 2007, Treher 2011, Berland 2011, Yoon 2014) thanks to some important characteristics:

1. The playful and immersive nature of board games facilitates attention, concentration and motivation of players;
2. In the course of the game the players experience a "suspension of disbelief" that prepares them to accept ideas even far from their everyday experience (Montola 2005, Walther 2005, Juul 2008, Zimmerman 2012);
3. Board games allow a "learn by doing" approach (Castells 2000, Prensky 2007) providing an hands-on and heads-on skill and knowledge development;
4. Thanks to competitiveness and will to win players are urged to deeply understand the rules behind the game;
5. Downtimes, which are characteristic in board games (for example in the waiting of the opponent's moves), together with the playful and competitive atmosphere promote reflections and discussions among players;
6. These downtimes also promote the inclusion of clarifications and explanations in a natural and not disturbing way by teachers or scientific animators during the game course.

In this paper we present some experiences in the development and use of board games expressly designed as game based learning tools for complex and abstract scientific concepts exploiting the abovementioned features. Differences from other similar experiences can be found in one or more specific characteristics of these games:

1. **Topics:** They are entirely focused on STEM subject (Science, Technology, Engineering and Mathematics), in particular on modern Physics and relatively abstract and complex concepts;
2. **Target:** They are designed for adults and high school students (they result playable also by kids, but this is not the main objective and we expect a lower effectiveness in this case);
3. **Goals:** They must encourage interest and curiosity, provide metaphors and examples to facilitate the comprehension of few fundamental complex scientific concepts, enhance understanding and learning using a playful, competitive and immersive context, prepare an open and receptive environment for a subsequent systematic treatment of contents;
4. **Method:** Selection of a small core of a very reduced number of key concepts that may enable and facilitate the understanding of the chosen topic; construction of the entire game structure, mechanics and rules with these concepts and around this core. In the context of this work we are not interested in games where the knowledge elements to be learned are inserted in the game as external, didascalic elements (as for example happens in game based on quiz). These rules must however remain simple and immediate despite the complexity of the inspiring concepts, and the game must be entertaining and enjoyable also in the absence of prior knowledge about the covered topics.

The game design process took place empirically, through trials, failures and repeated changes, exploiting some prior experience in the creation of "conventional" board games and always keeping in mind the above mentioned principles. Special efforts are always required to balance the functionality and playability with the educational needs, and this can be obtained only by a lot of tests and experiments.

The paper is organized as follows: we first present the three games we developed and their experimentation:

1. **"Quantum Race":** A board game designed to introduce some elements of Quantum Mechanics such as delocalization, state collapse, tunnel effect and quantum teleportation, used in high schools as motivational and teaching tool, and in occasion of science festivals and games festivals as a scientific dissemination tool;
2. **"Lab on a Chip":** A board game designed to explain the emerging nano-biotechnologies and the human immune system;
3. **"Time Race":** A game designed to explain relativistic concepts such as proper time and time dilation.

Then we present an emerging evolution of this activity, the experimentation on the possibility to use board game design as a learning tool by engaging learners in the creation of original scientific board games. A first attempt was done in occasion of the Italian "Festival della Scienza di Genova 2015", with a laboratory for the creation of board games on light, while presently it is progress a competition for Italian High School students for the creation of a board game on light and photonics.

At the end we trace conclusions on this activity, on the obtained results and issues and on the future perspectives.

QUANTUM RACE

In the microscopic world of molecules, atoms and subatomic particles the reality behaves in a manner very different from what happens in our familiar macroscopic world, with rules described by the Physical theory called Quantum Mechanics, which can result strange and very anti-intuitive (Gilmore 1995, Muller 2002, Sakurai 2011, Chiarello 2014). For example, an electron (which is an elementary particle of negative charge) in some cases appears to behave as a particle, well localized in a single precise position of space, but in other cases appears to behave as a wave, completely delocalized in space and so in several places simultaneously. This strange behavior is called "wave-particle duality" and it is common to all microscopic particles (protons, neutrons, but also photons, the particles constituting the light, and so on). Until the electron moves undisturbed it is well described by a delocalized wave (the so called "wavefunction"), but if an observer measures its position there is a sudden change: the electron returns to behave as a classical particle placed in a precise position, which is chosen in that moment in an absolutely randomic manner. This strange, apparently absurd behavior is called "collapse of the wavefunction". It can be interpreted in the sense that, while a classical particle can be at each instant only in a precise state of position (in a precise place), the quantum particle can be simultaneously in a superposition of different states of position, but if its position is observed the particle is forced to choose randomly only one of these states. The "tunnel effect" is another anti-intuitive quantum behavior: a classical particle cannot pass through a barrier (a barrier obtained, for example, by an electrostatic potential) but a quantum particle can do it or, to be more precise, in its delocalization has a non-zero probability to be also beyond the barrier. The states of position are not the only possible states for quantum objects. For example, an electron has an internal property called "spin", something that in a very descriptive manner can be thought as a sort of "inner" rotation of the particle. The undisturbed electron can be in a superposition of different spin states (just to give an image, it can simultaneously "rotate" clockwise and counterclockwise) but if one observe this property there is a sudden collapse in one of the two spin states randomly chosen and the electron returns to behave classically. This means that in general it is not possible to know all the details of a quantum state, consisting of a superposition of different states, since a measurement destroys this superposition and returns only one of these states chosen randomly. This is surprising, but more surprising is the fact that it is possible (and it has been experimentally done) to teleport this quantum state from one particle to a second identical particle without any observation (with absolutely no knowledge on the teleported quantum state). This operation, called “quantum teleportation”, destroys the state of the original particle and transfers it to the second particle.

The concepts described above (delocalization, collapse of the wavefunction, tunnel effect, quantum teleportation) are just a small part of Quantum Mechanics, but they are essential for an initial, coarse understanding of this theory. They all appear anti-intuitive and difficult to be accepted: Niels Bohr, one of the fathers of Quantum Mechanics, declared “Anyone who is not shocked by quantum theory has not understood it” (Barad 2007), and Richard Feynman, one of the greatest Physicist of the 20th century, affirmed: “I think I can safely say that nobody understands quantum mechanics.” (Feynman 1965).

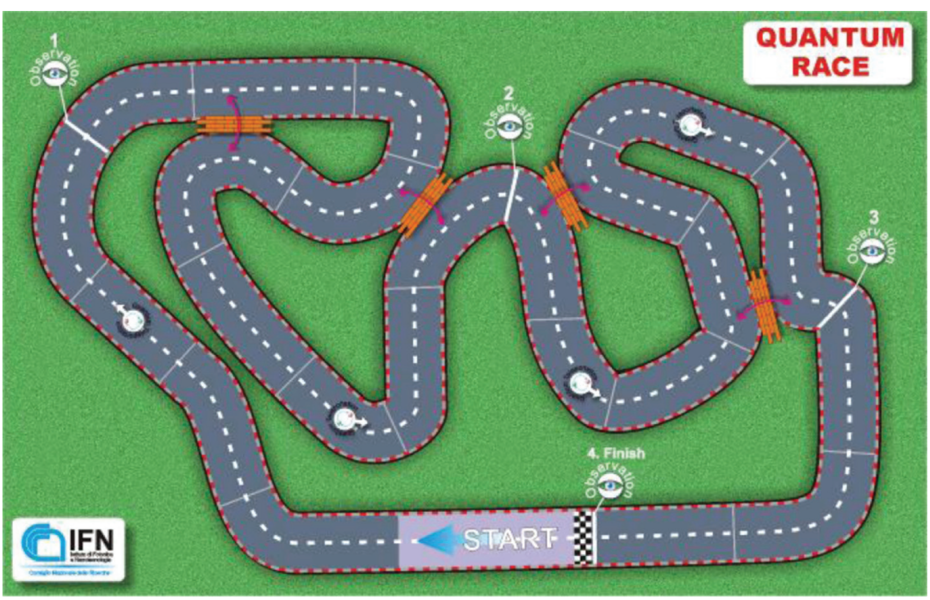
The game Quantum Race has been developed starting from these four concepts. We limited ourselves only to them in order to keep the game simple enough and to avoid an excessive load for the learner, but in the same time to give enough basic elements to understand what Quantum Mechanics is.

The game simulates a car race, with a board reproducing a racetrack divided in 24 cells, with a starting cell, a finishing line and some others elements that will be presented in Figure 1.

Each car is represented by six pieces, numbered from 1 to 6. At the beginning they are all placed in the same position, the starting cell, and in this case they represent a classical particle well localized in a precise position. During the game they can be scattered along the track reproducing the delocalization of a quantum particle. In the presence of an observation there will be a collapse: all the pieces will return in a single position randomly chosen. Let us describe the rules in details:

1. **Movement:** This is the first phase in each round and it is mandatory. The player picks all his pieces from a single cell and seeds them in the subsequent positions, one for position. For example, if there is a single piece in a cell the player moves it to the next position; if there are three pieces in a starting cell the player picks all of them and places one in the first next position, one in the second and the last in the third. This rule recovers the mechanism of the ancient African game “Mancala” (Wanderi 2011);

Figure 1. “Quantum Race” board game



2. **Tunnel effect:** Four "walls" separate close positions of the track in its sinuosity. The player can try to cross one of these walls by "tunnel effect": he declares the intention to cross the chosen wall, rolls the dice, and all the pieces of all players close to this wall and with the number just come out cross the wall in both directions. This action is optional and can be done only once per round;
3. **Quantum teleportation:** Along the path there are four teleportation pawns placed in different positions. The player can exchange one of his pieces in this position with an opposing piece ahead in the path that must have the same identical number. After this the teleportation pawn is moved back by one position. This action is optional and can be done only once per round, before or after a possible tunnel effect;
4. **Collapse of the state:** This action is mandatory and must be the last of the round. Along the path there are three observation lines, with an observer pawn initially placed in the first of them. When the first line is crossed by a piece a collapse occurs. The player rolls the dice and each player reconstruct his cars (all six pieces composing it) in the position where there is the piece with the number just come out. After that the observer pawn is moved to the next observation line, and after the third observation it is removed from the game;
5. **Winning:** The first player to cross the finish line with all his six pieces is the winner. The game ends when the pieces of all players cross the finish line.

These rules are very simple and can be explained in few minutes, and the game can be played by players from six years and over, with no previous knowledge about Quantum Mechanics. The game has been successfully played by a large number of players, essentially in two different contexts: schools and games/scientific festivals. In the first case we organized an intervention in Italian Scientific High Schools with a total of about 100 students at their last year (about 17 years old). The intervention was divided in two distinct phases: in the first phase the students played freely with Quantum Race. Right after, in a presentation strongly based on the game experience, the basic principles of Quantum Mechanics were introduced. This intervention preceded the curricular treatment of Quantum Mechanics made by teachers throughout the academic year. A direct contact with the involved teachers gave us a qualitative indication on the impact of this intervention. According to teachers, the students appeared to be strongly motivated (this was visible even right after the game session), with significant interest in the subject and with an increased ease in accepting and understanding abstract concepts relative to Quantum Mechanics, while the game experience provided an important help to teachers thanks to examples and illustrations. However a more quantitative analysis must be still addressed.

Quantum Race was also presented at different festivals, in this case for scientific dissemination to general public. It has been presented at the "Festival della Scienza di Genova 2011" in a live version, with a giant board of about 70 m^2 and participants moving as pawns on it, with a total number of about 1000 participants during all the festival (see Figure 2).

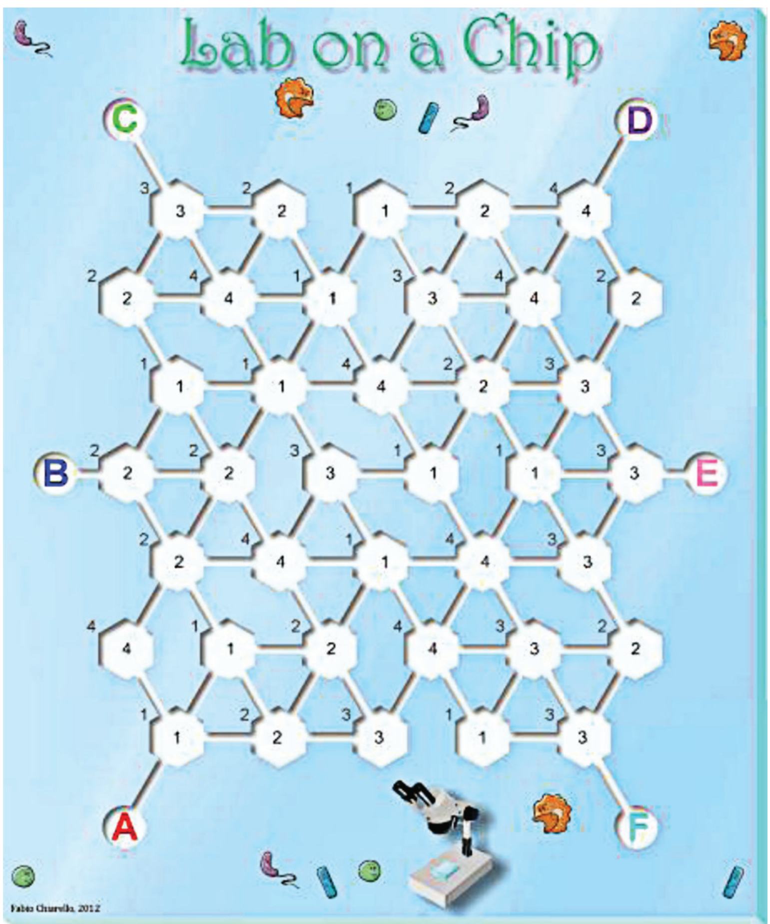
It has been also presented in a giant/medium format (about 10 m^2) at the games and comics festival "Carrara Show 2015", and at the European Researchers Night 2015 in Rome. A number of conventional tabletop version of the game were also played in occasion of the "Lucca Comics & Games 2015" festival. In all these case the players were assisted by scientific animators that first explained the game and then used the game experience to talk about Quantum Mechanics and to answer the numerous questions. The effect of the game (reported by the animators) was a fostering of curiosity and interest toward Quantum Mechanics and modern Physics topics in general, and a support in the explanation of complex and abstract scientific concepts thanks to the game play experience.

LAB ON A CHIP

Lab on a Chip (Figure 3) is a board game developed to explain the immune system and the use of nano-biotechnologies for its study (Chin 2007, Businaro 2013, Agliari 2014). The board game

Figure 2. "Quantum Race" live version at "Festival della Scienza di Genova 2011"

Figure 3. Board game "Lab on a Chip"



reproduces a "lab on a chip", an artificial labyrinth of micro-chambers and connecting channels realized by microtechnologies, where fluids and different cells are injected and interact under the lenses of a microscope camera recording what happens. In particular in this game it is considered the interaction (the war) between the macrophages of the human immune system and invading bacteria.

The players take the role of different kinds of bacteria or macrophages and move in the labyrinth according to simple rules:

1. Bacteria must cross the labyrinth, entering from one position and exiting from another position, both chosen randomly by drawing cards;
2. Macrophages must catch as many bacteria as possible;
3. The movement can occur between hexagonal chambers only through the connecting channels and by a number of steps indicated in the starting chamber;
4. The game is stopped after 30 minutes. The number of bacteria passed or caught is counted and this determines the winners.

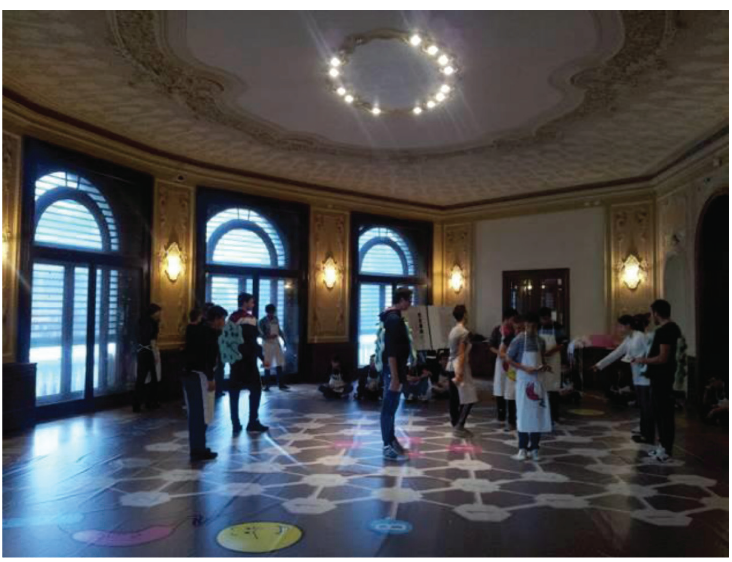
The game was played during the "Festival della Scienza di Genova 2012" by about 800 players, in a live version on a board of about 50 m^2, with the help of two animators involved in explaining the game and the underlying scientific concepts (see Figure 4).

Of course these concepts are not so complex and abstract as in the case of Quantum Mechanics, but also in this case the playful and immersive nature of the game resulted in a good impact on motivation and understanding of players.

TIME RACE

As described by the Theory of Special Relativity introduced by Albert Einstein (Einstein 1905, Einstein 2001), the flow of time is not universal: an observer moving at a very high speed with respect to another one experiences a slowdown in the flow of time as if every second were dilated. This is the so called "time dilation", a phenomenon well established and verified but far from our daily experience because perceptible only at speeds close to that of light, about 300 000 km/s. Unlike Special Relativity,

Figure 4. Live version of "Lab on a Chip" at the "Festival della Scienza di Genova 2012"



which considers the effects related to a uniform relative motion among observers, General Relativity considers also the effects of accelerations and gravity (Einstein 2001, Weinberg 1972). Actually time dilation can occurs also due to the presence of a gravitational field or, equivalently, of an acceleration among observers. For example, the flow of time is slower on the surface of the earth rather than in a satellite in orbit around the planet. This is a very small effect but it is visible and important if one considers the Global Positioning System (GPS), where the exact position on earth is determined by the comparison of time signals between satellites and earth clocks.

Time Race is a board game developed to "immerse" the players into the effect of time dilation and it can be used as a support for the explanation of Relativity. It is a simulation of a spaceships race, with a game board representing a racetrack consisting of a network of nodes connected by branches (Figure 5). Some branches present speed limits, simulating the fact that at higher speeds it is necessary to travel on more external and broader curves.

Each player drives a spaceship moving between connected nodes, and has a tachymeter and a clock. Here are the main rules:

1. Initially the ships are placed in a starting position of the track, with initial velocities set to one and clocks initialized to zero;
2. The current player can decide to maintain its speed or to increase or decrease it by one unit (with velocities ranging from 1 to 6);
3. Its ship is moved of a number of nodes given by the chosen velocity, taking care to respect the speed limits;
4. Its clock is incremented by a time interval depending on the speed, according to the values in Table 1;
5. When a ship crosses the finish line its clock is "stopped". At the end all the clocks are compared and used to define the ranking of winners.

Time Race gives the impression to experience the time dilation phenomena and can produce very didactic (and frustrating) paradoxes: the player who first crossed the finish line can lose the match having taken more time than others.

Figure 5. The game board of "Time Race"

Table 1. Time increments used in the game (column 2) depending on the speed (column 1). These values are approximated simplifications of the real ones (column 5), by supposing that in the fixed stars reference each round corresponds to time interval of 30 minutes. In the last column (column 6) there are the relativistic corrections, corresponding to the ratio between the time increments in the spaceship reference and the corresponding ones in the fixed stars reference.

Speed (Nodes/Round)	Time Increment (Approximated)	Corresponding "Real" Speed (Km/S)	Fraction of Light Speed	Time Increment (Exact Value)	Relativistic Correction
1	30'	45 000 km/s	15%	29' 40''	99.0%
2	30'	90 000 km/s	30%	28' 37''	95.4%
3	25'	135 000 km/s	45%	26' 47''	89.3%
4	25'	180 000 km/s	60%	24' 00''	80.0%
5	20'	225 000 km/s	75%	19' 51''	66.1%
6	15'	270 000 km/s	90%	13' 06''	43.6%

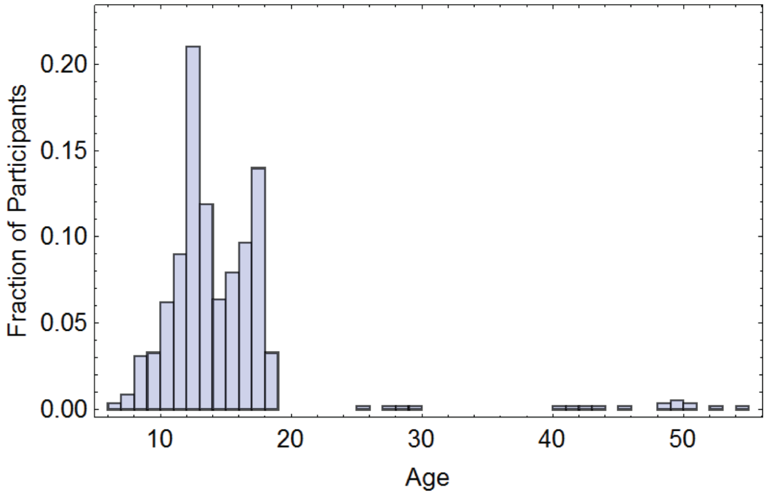
The game has been played by about 1200 participants during the "Festival della Scienza di Genova 2014" in a live version (about 40 m^2 game board, Figure 6), also in this case with the help of two animators explaining the game and, after each match, using the game experience to explain time dilation and Relativity.

At the end of each match the animators also distributed an anonymous survey containing general information (sex, age, occupation etc.), questions on amusement and appreciation, and a self-assessment on the comprehension of the presented topics before and after playing, based on a possible score from 1 to 5. A complete analysis is in preparation but we can anticipate here the main results. The survey has been completed by 591 participants (294 male and 297 female) with a mean age of 14 years (6 years the youngest, 50 years the oldest). In Figure 7 it is reported a histogram with the distribution of participants by age.

The question on amusement ("How much did you enjoy the game?") gave a mean value of 3.74 for men and 3.66 for women. The self-assessment was based on three questions, each of them considered before and after playing:

Figure 6. "Time Race" match in the live version at the "Festival della Scienza di Genova 2014"

Figure 7. Distribution of participants by age



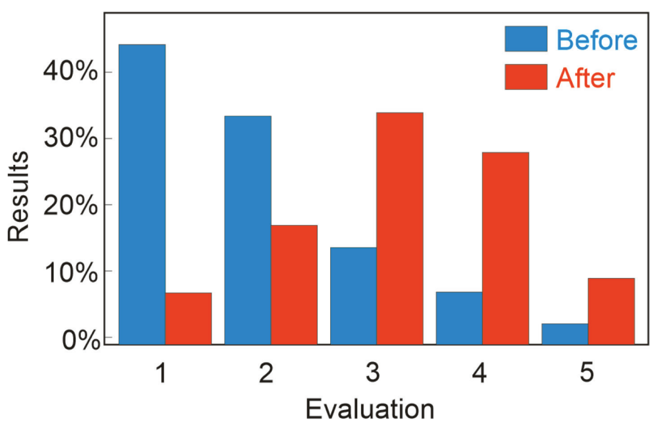
1. General knowledge on relativity (mean value before 2.06, after 3.37);
2. Awareness of the difference between special and general relativity (mean value**s** before 1.66, after 2.89);
3. Knowledge on the time dilation phenomenon (mean value before 2.06, after 3.29).

We obtain an overall average rating on the three questions of 1.93 (before the match) and 3.18 (after the match), with an increase of 1.25 points on 5 (a relative increment of 25%). In Figure 8 it is reported the histogram relative to the overall result, which points out the good impact of the game.

ENGAGING LEARNERS IN BOARD GAME CREATION: PHOTONICS GAMES

We are now considering a further step based on the direct involvement of students and general public in the creation of original scientific board games of the kind described above. The idea is to use this

Figure 8. Histogram showing the overall results of the self-assessment on the themes of "Time Race" before (blue) and after (red) the match



activity in order to foster an active thinking and reflection on a particular scientific subject, in this case the light. This is part of a wider project started at January 2015, the European Photonics4All Project, whose intent is the use of conventional and unconventional media for the awareness of people towards light technologies and photonics (Photonics4All 2015).

The laboratory "Photonics Games: Hands On" was organized in occasion of the "Festival della Scienza 2015" (see Figure 9). Its goal was the creation of original board games on the theme of light. About 650 participants (mainly students from 8 to 18 years) took part to the laboratory during the eleven days of the festival. The participants were divided in groups of five persons and two scientific animators assisted the participants during the session (90 minutes long) by presenting elements/suggestions on game board creation and on light, and distributing adequate material (paper, pencils and markers, dices, pawns of different kind and colors and so on).

Also in this case the impression was very positive: the attendees appeared motivated, sometimes enthusiastic, very curious about both the themes of games and light, and the invented games denoted a lot of imagination and **a** personal reflections on the covered topics. At the end of each session an anonymous survey was distributed in order to collect more quantitative data on the experience, but these data are not yet available.

A second activity, connected again to the Photonics4All project, is the Photonics Games competition. In this case Italian High School student must create original board games on light and on photonics and the best one will be awarded during the Archimede Prize (Archimede Prize 2016), the main competition for Italian board game designers. The competition, still in progress (the deadline is 31 January 2016), provides an excellent opportunity to contact interested students and schools in order to test the board game design as a learning tool.

CONCLUSION

We have considered the development and use of board games specially created as supporting tools for the understanding and learning of complex and abstract scientific concepts such as Relativity and Quantum Mechanics. The main idea is to consider only a reduced number of fundamental concepts enabling to the understanding of a considered topic, and to use them as "building material" and central core around which to build the entire game structure, in particular its mechanisms and rules, while keeping it simple. In this way the gaming experience becomes a way to "immerse" oneself in these concepts. There is not a sure recipe for the realization of games of this type, the design process was empirical, based on a trial and error approach and on a previous experience on board game

Figure 9. Laboratory "Photonics Games: Hands On" at the "Festival della Scienza di Genova 2015"

design, and successful results were obtained only after many attempts. The games have been tested in different contests, in particular in high schools, in science festivals and in games festivals, with good results in particular in:

1. Intriguing and motivating players towards the considered issues;
2. Catching the players interest toward explanations given by animators/teachers;
3. Giving examples, analogies and metaphors that have proved to be fundamental supports for learning and understanding;
4. Pushing players to a deeper understanding of the essential aspects.

We are now exploring the direct involvement of learners in the creation of scientific board games as a learning support for such complex scientific arguments. First results are encouraging, but more comprehensive studies are expected only for the next future.

In both cases (use of games and involvement in their design) a more quantitative and systematic analysis is required and a lot of work must still be done.

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The mission of the **International Journal of Game-Based Learning (IJGBL)** is to promote knowledge pertinent to the design of Game-Based Learning environments, and to provide relevant theoretical frameworks and the latest empirical research findings in the field of Game-Based Learning. The main goals of IJGBL are to identify, explain, and improve the interaction between learning outcomes and motivation in video games, and to promote best practices for the integration of video games in instructional settings. The journal is multidisciplinary and addresses cognitive, psychological and emotional aspects of Game-Based Learning. It discusses innovative and cost-effective Game-Based Learning solutions. It also provides students, researchers, instructors, and policymakers with valuable information in Game-Based Learning, and increases their understanding of the process of designing, developing and deploying successful educational games. IJGBL also identifies future directions in this new educational medium.

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