PIXEL: Challenges of Designing a Professional Board Game for Astronomy Education

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Abstract: PIXEL - Picture (of) the Universe is a board game developed by INAF - Italian National Institute for Astrophysics in collaboration with GAME Science Research Center. The game simulates the astrophysics research environment, particularly emphasising the observation and study of cosmic bodies at different resolutions. Image resolution is a crucial element in astrophysics, but the intrinsic complexity and challenges of making high-resolution images of the distant Universe are not easily and generally perceivable. We envisioned PIXEL driven by this challenge. Games intended to engage students with science either concentrate on the contents to foster the learning process or focus on life skills solicited by scientific practices. Game mechanics are then either a leverage of scientific knowledge or a science-like behavioural model, depending on the expected outcome of the game-based learning process. In addition to that, game-based learning in STEM (Science, Technology, Engineering, Mathematics) generally is designed by science practitioners and science communication and education experts. The design process of PIXEL has been a novel joint effort between scientists, science communicators, professional game designers, and game-market and award advisors. We produced a game in which the mechanics are the core of scientific learning, implicitly telling about science while making the player experience it. The innovation of this process is to obtain a game that encountered positive feedback both from the community of game experts and the educational context. The final output is a professional board game suitable for STEM education that promotes scientific citizenship in the audience. In this work, we discuss the game design process and describe how we included our scientific educational messages of image resolution and research dynamics as processes within the game mechanics without making them explicit during the gameplay. We also present a preliminary engagement evaluation of PIXEL and its efficacy in delivering implicit scientific messages through its mechanics.

Keywords: Game design, Game-based learning, Astrophysics, High school education, Intersection of professionalisms

1. Introduction

Many pedagogical studies have pointed out the effectiveness of play as an educational tool (Setiawan & Phillipson 2019; Yunus & Zaibon 2021; Nurtanto et al. 2021; Zourmpakis et al. 2022). In particular, the game-based learning (GBL) methodology has proved to be highly successful when applied to STEM education, reporting increased learning outcomes and better attitudes toward science in groups of students involved in GBL (Li & Tsai 2013; Setiawan & Phillipson 2019; Papadakis et al. 2023).

In the framework of the so-called game-based science learning (GBSL), the involvement with disciplines can be achieved through games making the subject more enjoyable and fun also for younger target ages (Zourmpakis et al. 2023; Zourmpakis et al. 2022), fostering a more permanent and effective learning process (Beltozar-Clemente et al. 2022; Campos-Pajuelo et al. 2022; Papadakis et al. 2023). On the other hand, players can practise many transversal and generic soft and life skills, not necessarily specific to the disciplinary content, such as problem-solving, communication skills, and teamwork. (Kirriemuir & McFarlane 2004; Qian & Clark 2016; Nurtanto et al. 2021; Sin Yoon & Khambari 2021).

As such, scientific thinking is one of the most relevant competencies that GBSL try to solicit through games. Scientific thinking skills are not merely limited to the scientific research environment but belong to our daily lives. In this framework, Morris et al (2013) introduced the concept of scientific literacy as "the skills that are

required by citizens in a scientifically advanced democracy". Barab et al. (2007) state that it is up to science education to help students to develop skills necessary for dealing with 21st-century challenges. According to these definitions, scientific "literacy" has very little to do with knowledge intended as a set of notions, and it is more likely to be interpreted as the awareness of the processes and paths that lead to scientific knowledge, building upon critical thinking and the scientific method.

Applying these ideas to GBL, game mechanics either can be unrelated to the contents of the expected learning process, only being the means of the gamification of sciences, or they can represent themselves as the learning object and an explicit reference to the discipline can help to put the process into context (Sin Yoon & Khambari 2021).

In this study, we argue that a game design focused on mechanics can be a powerful way to use games to empower learning and awareness of sciences. In particular, when they never use disciplinary prerequisites to proceed and succeed in the gameplay nor ever introduce the verification of the disciplinary learning outcomes.

For this aim, game mechanics must mimic specific topics to be effectively experienced and not confusing. A multidisciplinary approach is needed, involving different research professionals to best focus on the contents (Yunus & Zaibon 2021, Sin Yoon & Khambari 2021).

Most importantly, game mechanics must keep the game faithful to its nature, of a playful environment not aimed at learning, but in which learning happens, almost by chance, wanted but undeclared (Toniolo et al. 2023). For this aim, a professional game designer, not only an expert in educational gamification, should be a crucial character in game design.

With this in mind, we designed PIXEL-Picture (of) the Universe, an astronomical-themed board game with the aim not to teach astronomical content but to improve the development of scientific thinking skills in players and also to engage the general public with the world of scientific research and Astrophysics. To reach this goal, the design of PIXEL was a multidisciplinary collaboration between astronomers of INAF - the Italian Institute for Astrophysics and professional game designers of the GAME Science Research Center. The final product is a board game in which we tailor the mechanics to reproduce astronomical observations at incremental resolutions and realistic research processes of an observatory, such as technological development, multidisciplinary research team, and publications. In this way, we let players have first-hand experiences of such scientific concepts and processes by playing with them and using them as a central part of their strategy to win the game.

This paper is structured as follows: in Sec. 2, we show PIXEL in detail and introduce how to play the game. Section 3 exploits the multidisciplinary design process, stressing how we balanced scientific content and the fun of the game. We achieved this result by implementing specific game mechanics that mimic astronomic scientific concepts and processes, as described in Se. 4. In Sec. 5, we present the feedback we collected to test PIXEL entertainment and scientific engagement, and we summarise our conclusions and introduce future developments for this project in Sec. 6.

2. PIXEL: Description of the Game

PIXEL-Picture (of) the Universe is a board game developed by astrophysicists of the Italian National Institute for Astrophysics (INAF) in collaboration with Andrea Ligabue, a professional game designer, game-market and award advisor of the Game Science Research Center.

PIXEL is a competitive game of 60-90 minutes for 3 to 5 players designed to simulate the astrophysics research environment, with particular emphasis on the observation and study of cosmic bodies at different resolutions.

We envisioned PIXEL for GBL activities in secondary schools for students 14-16 years old, but the final target of PIXEL also includes board gamers and board game lovers beyond the educational scope of the game, lowering the minimum target age besides the GBL activity to 12-13 years old.
In PIXEL, each player has to manage an observation research centre to observe three celestial objects, such as galaxies, nebulae, and objects of the Solar System.

As the game proceeds, each player shall manage Resources and the Research Centre to lead the researchers ' team, specialise them, improve the laboratory, publish, and observe more and more portions of the Universe using their Ground and a shared Space Telescope, gaining the points that will determine the winner at the end of the game.

Figure 1: PIXEL played at PLAY game festival 2023

To observe the celestial bodies, the players place and flip tiles corresponding to different portions of the celestial bodies in the game at incremental resolutions. We have four different resolution levels of the Celestial Objects and, as the resolution goes higher, the players will discover more and more details of these Objects and solve their goals and projects, as shown in Fig. 2. To observe at higher resolution, the player shall improve the resolution power of both the Ground and Space Telescopes they have available for their observations.

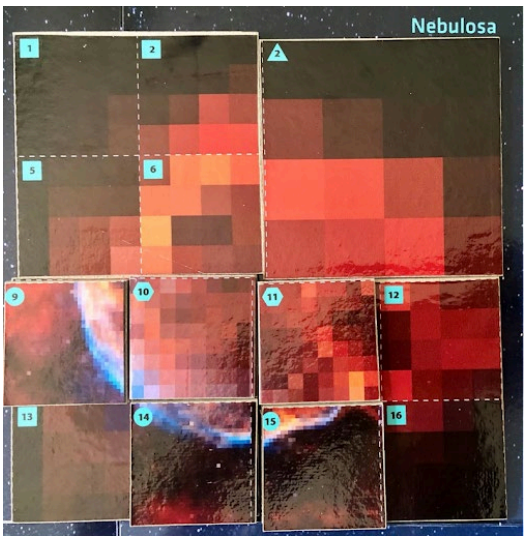

Figure 2: How an image of the Medulla nebula is reconstructed during the game. The symbol in each tile identifies the resolution. From the lower to the higher: triangle, square, hexagon, circle

2.1 How to Play

In this section, we introduce how to play PIXEL. A complete description of the game's rules can is available at the following link: https://youtu.be/yYwoGZCmkkU

During the setup of the game, each player obtains a Research Centre to manage, starting from Level 1, with 5 Resources, a Ground Telescope at Level 1, an Objective card corresponding to one of the Celestial Objects used for the game, 2 Project cards, and 3 Researchers.

The Objective cards represent the main individual observation goal of the game; on each Objective card is indicated a specific resolution tile of a Celestial Object. At the end of the game, if that tile is revealed, the player with the Objective card scores points according to how much they observed the Object during the game. The Project card instead gives points during the gameplay when players accomplish specific observations or

technological development of their Research Centre. Finally, the Researchers allow players to make actions in the Action phase of each turn.

Every PIXEL game goes on for four turns. Each turn is divided into four different phases: the Preparation phase, the Action phase, the Observation phase and the Publication phase. At the end of the four turns or when someone reaches the common goal, the game ends, and players calculate the Scientific Prestige (SP) points. Who scores the most SP points wins the game.

In the Preparation phase, players collect Resources to invest in their actions, obtain new Project cards, and the turn order changes in inverse order of SP points. Then, an Event card is revealed and immediately applied for the current turn.

In the Action phase, players use their Researchers to carry out one action at a time while spending the relative Resources. There are several actions available: for example, improving the Space and Ground Telescopes, booking the use of the Space Telescope for this turn, specialising or hiring a Researcher, buying new technologies, and publishing.

In the Observation phase, players use their Ground or Space Telescopes to observe one or more portions of the Celestial Objects. An observation consists in placing or flipping a tile of the specific Object according to the resolution allowed by the level of the Telescope in use. As players observe a specific Object, they advance in the Observation Grid of that Object, at some points gaining SP points and Publication cards of that category.

Focusing the observation on a specific object is also crucial in the final Publication phase of each turn, in which players obtain one extra Publication card connected with the Object category in which they lead observation, such as Galaxies, Nebulae, and Planets. At the end of the game, Publications will give SP points according to how much players focus on the same category or collect cards of different categories.

3. The Design Process

PIXEL is a multidisciplinary collaboration between INAF astronomers, who want to disseminate astronomical and scientific knowledge, and GSRC game designers, who want to create an engaging and feasible board game. For this reason, the co-design process sometimes compromises different choices and premises but enriches each other's views and ideas. Each implementation was discussed, balanced and playtested.

The basic idea of PIXEL arose from the playful hands-on activity for 9 to 10 years old children named ‘‘Talking about Resolution” (Varano & Ricciardi 2018; Ricciardi et al 2019) developed by INAF researchers. During this activity, participants have to recreate a recognisable image for their mates in the less time possible. To do so, they have to choose and insert pegs of different colours and sizes in the holes of a board (Fig. 3). The pegs are intended to represent the pixels of a digital image.

The main goals of this activity are:

- to introduce core concepts of astrophysical imaging (such as spatial and chromatic resolution and sampling); without explicitly introducing them, leaving much space for personal intuition and autonomous discovery;
- to encourage all children's commitment through playing thanks to familiar toys.

The activity was tested in several contexts between 2018 and 2019, such as schools, interactive science exhibitions, and events dedicated to science outreach. "Talking about Resolution" received positive feedback, and facilitators noticed a deep engagement of children with the processes and challenges of image representation through image units. As a follow-up to this activity, a master thesis analysed the activity within the framework of the game-based learning methodology, intending to identify its strong points and include them in the design of a board game (Varano & Toniolo 2021).

As a result of this work, we decided to design a board game around mechanics that lead to the construction of an image at different resolutions.

The game was meant to be engaging and entertaining, before (or better without) being educational.

In addition to that, as in "Talking about resolution", the main goal of the design remained to keep clean of foreword astronomical concepts to succeed in the gameplay and leave them to be autonomously (and possibly unconsciously) extrapolated by the game experience. That’s why we asked for the collaboration of a professional game designer, alien to the astronomical research field.

Figure 3: In the activity "Talking about Resolution" children use pegs of different sizes and colours to represent the image located under the board.

The first issue we faced in the game design process was the idea, suggested by the game designer, to reinsert an astronomical setting to take advantage of the fascination this branch of knowledge benefits in the public imagination and also to better stick to our public image, being this the ‘‘brand" expected for an activity proposed by an Institute of Research in Astrophysics.

With this choice, we abandoned the idea of using familiar images and presenting the concept of image resolution as general and transversal to all disciplines, linking specifically the process to astronomy. In this way, we lost the materiality of using pegs as pixels because of the impossibility of recreating recognizable astronomical images with sufficient resolution using pegs or other material units for each pixel. To preserve some materiality in the game mechanics and simultaneously reach a higher resolution for astronomical images, we introduced the innovative tiles mechanisms we described in the Observation phase of the game (see Sec. 2.1). In this way, we reproduce 4 different images of the same objects at incremental resolutions, from 8x8 pixels divided into 4 tiles, up to 128x128 pixels divided into 16 tiles. This choice brings benefits in terms of appearance, replicability and spread of the resolution mechanics in the game.

The choice of using astronomical images pushed us to design the board game to target higher ages concerning the activity ‘‘Talking about Resolution", from 12-13 years old to adults.

We analysed several board games already available in the market (Inchingolo et al 2023; Cardinot & Fairfield 2022; Engelstein & Shalev 2019) and started implementing more suitable mechanics that would lead to building images at higher and higher resolution. One of the most inspiring games we considered was "Genotype: A Mendelian Genetics Game" [Genius Games], which allows players to simulate research in Genetics, combining worker placement and resource management mechanics to carry on their research using specialising cards to draft players' facilities. We noticed that worker placement and resource management mechanics can be generalised to simulate any scientific research process. Using these mechanics, we tailored game actions to represent astronomy research processes like technology development, hiring new researchers, and more.

The role of professional game designers in this phase was crucial to transpose in efficient game mechanics the information provided by the astronomers about how astronomy research works. We jointly and accurately studied the correspondence of each character and action with the actual astrophysical research, ending with introducing in the game people and processes and their specific roles in obtaining the scientific results. In Sec. 4 we detail the correlation between the game mechanics and the related astrophysical concepts.

These concepts are implicit in the game, sticking to the initial idea of a game fostering autonomous learning instead of promoting it. For this reason, we design the mechanics to require no former knowledge to proceed in the game.

We introduced in PIXEL also explicit disciplinary aspects, by using descriptions and images of actual astronomical objects in Publication cards and the cards presenting the celestial objects available for the game. These elements are optional and not connected to the game mechanics.

A crucial part of the design process was the extensive time we spent in playtesting these mechanics, balancing the resource cost for each action and their effects, improving the scoring system and minimising micro-management, which otherwise would have distracted too much from the scientific process and the core goal of observing the objects in play at higher and higher resolution. In particular, we want to underline the importance of testing the game with targets of different game experiences and scientific backgrounds or interests. In this way, we collected feedback about not only the learning PIXEL fosters but also (and perhaps mainly) about the engagement and entertainment experience while playing.

While going through the design process, we decided to use the most gender-neutral language possible to show that science can overcome gender barriers. Being Italian the design language, this was not an easy operation since most of the words have only male and female versions, and the tendency is to use the male version for collective and generic reference to characters. For example, the translation of ‘‘researcher” is ‘‘ricercatore” (male) and ‘‘ricercatrice” (female), while ‘‘researchers” is usually translated as ‘‘ricercatori” (male plural). To help us with this matter, we collaborate with Vera Gheno, an Italian socio-linguist expert on inclusive language. As a result, we reduced the use of gendered sentences, preferring alternative but still natural-sounding paraphrases. When this was not possible, as for the example above, we introduced in our game the symbol “ə” (shwa), which is one of the suggestions to make words gender-neutral and overcome gender-binary references: in our example, the translation of both ‘‘researcher” and ‘‘researchers” will be ‘‘ricercatorə”.

4. Correlation With Astrophysics

The novelty of the PIXEL design process is how we design game mechanics to stimulate scientific pondering during the gameplay instead of delivering scientific knowledge using the game theme and contents. In this section, we detail the correlation between PIXEL mechanics and their relevance to astrophysics research and processes.

We drafted the mechanics to communicate and explain how astrophysical image resolution and scientific research environments work.

PIXEL theme and mechanics recreate the environment of astrophysics research and relations: players make decisions autonomously and collaborate with others, as in actual research. They have to combine different professionals to improve the level of the instruments of the research centre. They have to manage the observation time and resolution to choose whether to study small details at high resolution or the entire body at low resolution. As in actual research, results are shared with the community (in this case, the other players), and publications help obtain more winning points.

We kept the mechanics as relevant as possible to the reality of the research environment, without the presumption of being a realistic simulation, still offering players as many possible cues for thought. For example, in PIXEL each player has a specific observative goal to reach (the Objective card) connected with a particular portion of the Celestial Objects in the game. In actual Astrophysics research, we do not often know a priori where to observe specifically to obtain our scientific results, but this mechanic simulates high-resolution observations resting on the results of previous low-res general surveys.

Table 1 collects all the mechanics we designed to simulate how observation works in astrophysics, with particular emphasis on image resolution and technology development necessary for the observations. For all these mechanics, we explain the connection with Astrophysics research.

Table 1: Analogies between game mechanics (left) and astrophysics research (right)

Game Mechanics	Correlation with the Astrophysics Research
Highest-resolution tiles are smaller than the lowest-resolution ones.	Obtaining an image of high resolution requires more observation time, which corresponds to placing a tile in the game.

Game Mechanics	Correlation with the Astrophysics Research
Observations can be obtained both with a private telescope (ground) and with a public one (space).	Astrophysical research can be both competitive (for example when trying to be the first to observe a phenomenon) and collaborative.
Doing an observation gives an advantage to the player who made it, but the tile revealed on the board is available to all players.	Being the first to study a specific object gives an advantage to the researchers and their research centre, but data and the results obtained by the observation are shared with the scientific community.
Improving the public telescope needs fewer Resources than improving the private ones.	Public telescopes are the results of international or global collaborations.
Ground observation can be affected randomly during the game by good or bad observational conditions, while the Space telescope is immune to this effect.	Atmosphere conditions affect ground observation, while observations made with space telescopes are immune to these effects since they orbit above Earth's atmosphere.
Investing in the technological development of telescopes and their research centre allows for observing higher-resolution images.	In Astrophysics research, we constantly invest in technology development to improve the study of the Universe with more-detailed observations.
To place a higher-resolution tile, the corresponding lower-resolution one needs to be already observed on the board.	We reproduce the idea of astrophysics research that requires often a low-resolution study of a portion of the Universe (called "survey") to locate the interesting spots where to focus for a more detailed study with higher resolution observations.

In Table 2, instead, we collect all the mechanics we introduced to correlate with how astrophysics and the scientific research processes work, like the management of the research centre, research activities, and publications.

Table 2: Analogies between game mechanics (left) and research process (right)

Game Mechanics	Correlation with research dynamics
Every player has several researchers available to do his/her actions.	Scientific investigation is a collaborative and team effort of researchers, not a stand-alone activity.
The researchers can be specialized in different professionality, like theoretical, numerical and observation experts, project managers, engineers, and communication experts.	The management of a research centre requires a team not only of researchers but of many professionals that help with fundraising, communicating with the public, and implementing new technologies to progress in the research.
The number of Publication cards gives SP points at the end of the game.	Publications are a way to communicate each own investigation within the community and increase the scientific prestige of the centre.
Lead the observation in a specific object lets players gain Publication cards connected with the category of the observed object.	Focusing the research on a specific topic and category will improve your chance to publish on that topic and gain Scientific Prestige.
Resources are not a way to directly collect SP points.	A capable research centre is not one with more resources but with higher scientific prestige.

Game Mechanics	Correlation with research dynamics
Events at the beginning of the turn can affect players' strategy during the game.	Not always scientific research can be done as planned, but often researchers need to adapt their studies to external events.

5. Engagement and Scientific Stimulation Efficiency Evaluation

We designed PIXEL aiming for a professional and engaging board game in which astronomical contents can emerge through game mechanics during the gameplay. We test this purpose with a questionnaire after a single gameplay in different public events, like the 2021 and 2022 PLAY Game Festival in Modena, the 2021 and 2022 Lucca Comics and Games, and the 2022 and 2023 Science Festival in Rome. The scope of this questionnaire was not to test PIXEL's efficiency as an educational tool. Instead, we want to verify PIXEL enjoyment and appeal for teenagers and young adults (16-25 years old) with experience in board games. Simultaneously, we want to investigate how players may perceive the scientific contents we embedded in the mechanics.

To evaluate the engagement, we asked more than 200 people to assign a score on a Likert scale from 1 to 7 to several attributes about Pixel, both positive and negative responses. We evaluate the following PIXEL characteristics: funny, not attracting, absorbing, pleasant, boring, interesting, and entertaining.

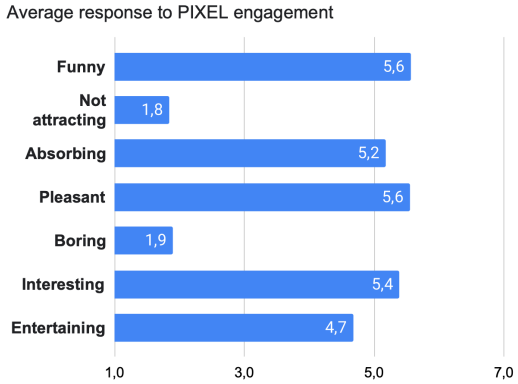

Figure 4: Likert scale for average response to PIXEL engagement.

Figure 4 shows the average engagement response. For our sample, the game is overall funny (5.6), pleasant (5.6) and interesting (5.4).

We put the “inverted” values of the responses to the three negative attributes to average them with the Likert value of positive attributes. For example, for the “boring” characteristic, we used the value 7-1.8=5.2 to average it with the other positive characteristics. In this way, we obtained positive feedback about the engagement and entertainment of PIXEL, with an average of all the attributes of 5.2/7.

We also asked the same 200 people for their feedback on our design aim to stimulate scientific topics within game mechanics. To do so, we created a list of 10 different scientific statements, 7 of them relevant to the science implemented in the game’s mechanics (as discussed in Sec. 4 and listed in Fig. 6). We request our sample to indicate the three sentences that are better referred to the game.

The probability of randomly answering our survey with at least one relevant sentence is 7/3, giving a random ratio of relevant/not relevant sentences to 2.3. From the collected answers, this ratio increased significantly to 13.6.

Figure 5 shows the normalised occurrence frequency over the 600 answers collected (3 for each of the 200 people) for each of the 10 statements. We observe that the most frequent answers are “Improvement of technologies brings to an improvement of observation resolution” (19,8%), “scientific research is a collaboration of different professionality” (16,3%), and “high-resolution images require more observation time” (14,9%).

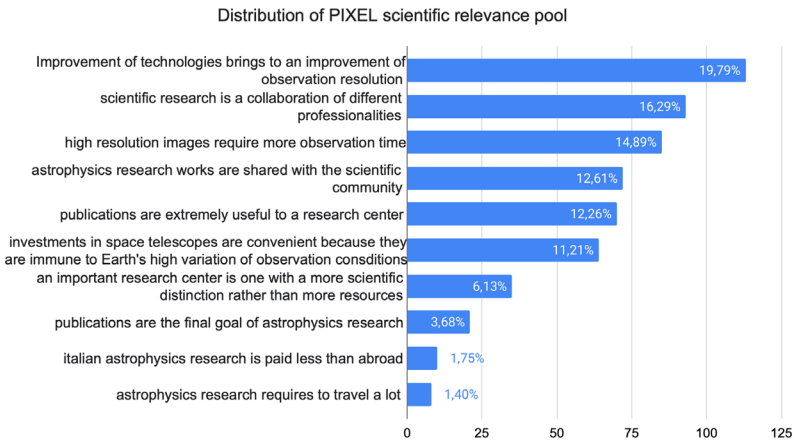

Figure 5: Normalised distribution of answers to PIXEL scientific evidence survey.

We conclude that PIXEL can stimulate scientific content in astronomy through its game mechanics after a single gameplay. In particular, people noticed the correlation between image resolution, and the required observation time and technological development necessary to get that resolution. Players also perceived the collaboration of different professionals as crucial to run an observation centre.

6. Discussion and Future Work

PIXEL - Picture (of) the Universe is an innovative astronomy board game we designed to be engaging and entertaining for a target of 16-25 years old without previous knowledge of Astronomy. We envisioned PIXEL as an educational tool for GBL activities in high schools. Contrary to most available educational games, in which the educational topic is explicit, in PIXEL, the mechanics are the core of scientific learning, implicitly telling about science while making the player experience it.

PIXEL was a co-design result between INAF astronomers and game designers of the GAME Science Research Center. In this work, we described the design process, emphasising how we balanced the engagement and entertainment of the gamer and the necessity to include actual scientific concepts and research processes. As a result, we embedded in PIXEL game mechanics the astronomical concepts of image resolution and how an astronomical observation centre works.

We shared the PIXEL design process since collaborating with game designers is not a diffuse opportunity in educational environments. In particular, it is possible to generalise some of the conclusions of this design process to other STEM disciplines helping other GBL practitioners in designing their games. For example, the game mechanics of worker placement and resource management are perfect for simulating any scientific research process, not only the astronomy one.

Another practice we learned from the design process was the necessity of testing the game with our teenager and young adult targets until we converged on a game suitable for our educational and engaging porpoises. For this reason, we collected feedback on these porpoises with a questionnaire after a single PIXEL gameplay in different public events, obtaining from more than 200 people a positive score of 5.2/7 on average. Same people confirmed our design idea of stimulating scientific thought with PIXEL, answering that in the gameplay, they noticed the correlation between image resolution and the required observation time and technological development necessary to get that resolution. Players also perceived the collaboration of different professionals as crucial to run an observation centre.

The positive feedback indicated that PIXEL is a professional board game that promotes scientific citizenship in the audience.

To test the efficiency of PIXEL as an education tool for GBL activities, we developed a long-term education project in 5 different high schools in Italy. We are currently working on data analysis and we will present the results in future works.

We understand some of the limitations connected with this co-design process. First of all, the time and economic investment in PIXEL production may limit the accessibility and distribution of the game, especially considering

the diffusion of digital and video games in society and education. Without sacrificing the materiality of the board game, we are currently working on a print&play version of PIXEL that will ease its usage in educational environments.

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