Graphical interface adaption for children to explain astronomy proportions and distances

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ABSTRACT

Mobile Science Center is a Polish project that seeks to bring astronomy knowledge to wider social groups through various applications. In its development it is necessary to design a graphical interface that explains a concept that is difficult to assimilate such as spatial proportions and distances. This paper develops a framework to create graphical representations that explain this learning to the target audience of children. Important aspects of this interface are the inclusion of storytelling to guide the educational content, along with feedback and difficulty and accessibility adaptations. Regarding spatial representation, previous works highlight the use of shapes and geometric objects, cartographic tools, reference points, and comparison with known velocities and spaces. The graphical interface proposed is based on a decimal system scale that compares traveling at the speed of light with a person walking. There are 4 proposals that represent the units of this scale with different geometric shapes and interrelated structures, in addition to assigned colors and positions. Future development of this project will apply these ideas to identify the optimal graphical interface so children can learn spatial proportions and distances.

Keywords

graphical interface; interface adaption; astronomy education; STEM education; science centers;

1. INTRODUCTION

Digital applications for STEM (Science, Technology, Engineering and Mathematics) education have been developed in recent years with very positive learning results. Using devices such as smartphones or computers, in addition to gamified interfaces, makes learning more attractive, especially for children. However, one of the branches of science for which these tools have been little applied is astronomy. Understanding the universe is vital to foster care for the Earth, understand human origin and develop critical thinking about pseudo-sciences. Primary education gives a basic knowledge of astronomy, but advanced knowledge is offered by science centers, which are generally located in big urban agglomerations. The location and non-digital format in which this information is offered can make it difficult to access and understand.

Recently, the project "Development of pioneering technologies necessary to launch the Mobile Science Center on the market and preparation of a prototype of the solution" has been created for the implementation of astronomical and astronautical learning applications in Poland [Kam20]. The objective is to guarantee access to wider social groups through the Mobile Science Center, with a specific interest in attracting children to this branch of STEM. For this goal, a total of 15 demonstrative stations have been developed in the first phase. Each application can be handled by non-qualified beginners, deepening their basic science understanding of astronomy, space exploration and space missions.

This project represents a challenge, not only due to the development of 3D modeling, physics and programming, but also for its graphical interface design. Space concepts can be difficult to represent and understand, especially those related to astronomical proportions and distances. Interpreting celestial and planetary maps is difficult for

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inexperienced people in this research area [Kar19, Tri18]. Realistically calculating the sizes of space orbs and the distances between them is complicated by the lack of reference points that we are used to on Earth. When we look at maps or terrestrial images, we have human constructions (roads, cities) or geographical features (mountains, lagoons, beaches) to estimate the sizes of what is represented [Har15]. In fact, a land surface without these human or natural landmarks makes interpretation of the scales extremely difficult [Hei07].

Of the 15 applications in the project, 4 require an understanding of astronomical proportions and distances. Their descriptions are as follows:

- *Solar System's virtual tour* (Fig.1). This application shows the path of a spacecraft between the different planets of the Solar system. Its aim is showing the different distances and proportions between these celestial bodies, in addition to the time necessary to make each trip.
- *Hohmann's transfer.* The application's aim is to explain the maneuver required to move a spacecraft from one circular orbit to another using the minimum amount of fuel. For this purpose, it is necessary to understand, apart from concepts such as force and speed, the distances between orbits.
- *Constellation's composition.* This application explains how to recognize different constellations and how they are composed by different stars. It also seeks to show the real distance between the stars, although from Earth they are seen on the same plane.
- *Interactive hologram of the Milky Way.* This application shows what a spiral galaxy looks like and where the Sun is located in the Milky Way. Distance and proportion understanding of Solar System in relation to the galaxy is another goal.

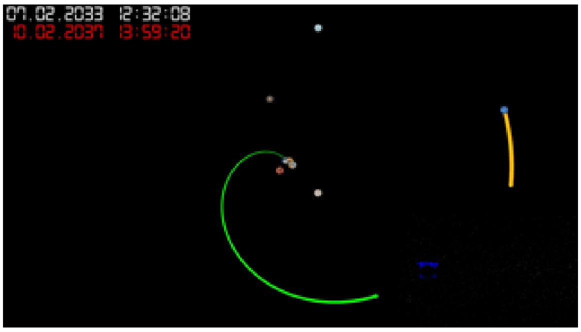


Figure 1. Screenshot of actual prototype of Solar System's virtual tour.

After completing the first phase of the project, prototypes for each application have been developed. Currently, prototypes fulfil basic operations and representations of each educational goal as Figure 1 shows. Nevertheless, for its final implementation, it is necessary to design a graphical interface capable of explaining spatial distances and proportions. Therefore, this paper develops a framework to apply a common interface to spatial representation, with 2D and 3D animations, so children can understand it. The result are different proposals that the work presents and discusses to implement to the final applications.

2. METHODS

To develop the framework that represents spatial proportions and distances, it is necessary to review previous works on Results section. On the one hand, it is studied what specific requirements serve for graphical interfaces with educational purposes that are aimed at children. These aspects take into account the tactile devices that will be used in the Mobile Science Center and its interface elements. The introduction of narrative and its relationship with the learning content are also considered, as well as the graphic representation of distances that are traditionally used. Finally, the importance of feedback and the adaptation of applications to different users are included.

The other part of the review has to study previous astronomy applications with educational goals. Their educational contents are checked and those that have represented spatial proportions and distances are analyzed. The graphic representations of these distances and the relationships between the celestial bodies' proportions are studied, as well as the explanation that the projects' educators have introduced. Any type of interactions that the applications allow the user are also analyzed, along with the changes and choices that occur in the interface as a result. This process gives keys to apply to the framework since they have already demonstrated their educational usefulness.

Once the theoretical bases of the design of this graphic interface project are reviewed, its development proceeds on Discussion section. It begins by defining its virtual elements and the basic interactions with the touch screen that all applications will have. A storytelling is also developed that will be applied to the entire project and will guide the user through all applications, along with the feedback and adaptation of content. Next, the graphical keys that have been obtained from the study of previous astronomy applications are developed to lay a foundation for this framework.

The scale in which the different distances and proportions between celestial bodies will be represented is defined. This scale has the same ratio of proportions in all applications and each of its units is assigned a color that remains the same. From this basis, this paper develops different proposals to graphically represent these relationships using distinct geometric shapes. Its inclusion and interaction with the users to achieve the educational goal is explained. Finally, the adequacy of each proposal for its future implementation in the final phase is discussed.

3. RESULTS

3.1 Design of children graphical interface

Graphical interfaces must take into account their target audience in its design process. This project seeks to represent astronomy proportions and distances so that children understand them. The applications are designed to be installed and managed in a Mobile Science Center, so users will have touch screens. These devices, to which children are accustomed from their first years of life, offer a direct and natural interaction with the digital contents. Tactile devices offer positive learning experiences that bring STEM subjects closer [Str20] and allow better spatial visualization than other types of interfaces [Bay18]. Children are able to directly interact with virtual objects and agents from the applications. There are also widgets such as buttons, controls and labels that offer different information and generate events with user's interactions [Bot16]. Children can use a finger to tap the desired options, or two fingers to move through the visualized space.

A main aspect of graphical interfaces that has shown great utility for children's learning is the inclusion of storytelling [Ber18]. Introducing information about spatial visualization and mental rotation skills through a story facilitates understanding and assimilation [Bay18]. Children associate the app's sequence of events with the educational goals they achieve. These should be reinforced with positive feedback when the user is solving a problem, so they also feel that they need this knowledge [Str20]. In addition, narrative is also perfect to guide the application management. Giving them too instructed use, or on the contrary a completely free use, can cause the user boredom or stress. However, story encourages exploration of virtual content and involvement of users with learning [Bay18]. Instead of passive observation, children actively practice with STEM experiences [Str20].

Regarding representation and understanding of spatial distances in a graphical interface, previous works have used shapes and geometric objects as well as patterns. The most common, in a two-dimensional or a three-dimensional way, are lines, points, spheres, squares, triangles, cubes, and cylinders [Bay18]. Children learn mathematics and spatial visualization from school with this type of manipulative objects. When they grow, these primitive forms continue to be a learning base on which other concepts can be fixed. When these are related to abstract thoughts, such as astronomical distance, concrete associations with the world are built [Str20]. To make it easier for them to differentiate, the chosen objects should have different shapes, colors, and scales [Bay18].

Finally, design of applications for children should adapt their content to the user's capabilities [Alm17]. If the users show difficulties in any of the events, they will be offered indications and reinforcements so that they can achieve the educational objective as well. These aids are a type of feedback that can be included in the narration, animations or sound effects [Bay18]. Using sounds with different timbres and rhythms, which fit in with the diegetic world of the application, will reinforce learning. However, for users with possible auditive issues, subtitles have to be added to all the narration of the application, as well as visual effects that match the auditive ones [Pir21].

3.2 Previous astronomy representations

There are some educational projects that have simulated the Solar System so that students could gain a better knowledge of astronomy. Kurniawan et al. [Kur12] designed the Space Exploration 3D game that visualizes and simulates space travel to challenge and engage children. The game is based on the Celestia 3D program, in which the user can travel at different speeds, from 0.001 m/s up to millions of light years/sec. Celestia allows to display space objects in three dimensions, in a scale ranging from a small spacecraft to the entire galaxies, and to interact with them. The learning objectives were the names, shapes, sizes and order of the planets in the Solar System, as well as comparing the rotation period and the revolution period of each planet. This application was pioneer to give the opportunity to realistically visualize the planets while showing their data so users could recognize them. However, this game did not offer a way to appreciate spatial distances and proportions, which is this paper purpose.

The issue of explaining the size relationships between planets was addressed by Gede and Hagitai [Ged17], who were aware that planetary maps are usually produced by astrogeologists for other professionals, but not for the general public. However, in the field of geography, outreach websites, applications and games for cartographic learning are common [Sim11]. Therefore, these authors applied planetary spatial datasets to design a web application for students, which uses cartography as a framework to aid virtual exploration of Solar System planets and moons. The learning goals were the interpretation of sizes and distances in these celestial bodies and the acquisition of extraterrestrial planetary geological knowledge in order to better understand the uniqueness of the Earth.

For this purpose, this application used the concepts of comparison of sizes, as well as of distances by calculating travel time. Since it is easier to estimate the size of an area when we can compare it with reference points, they took as a measure the size of the country of origin with which users are familiar. The application allows you to choose any country in the world and represent it on the surfaces of the planets of the Solar System, thus differentiating the size of the orb. Regarding the representation of distances, the user can form a straight line of desired length on every planet; then the app will calculate the time it takes a person, a Mars Rover, a spacecraft and a car to travel it with their different speeds. The tool does not take into account the topography or the surface of the planet, but allows a realistic estimation of the required movement and time in a space mission.

Another project developed to promote STEM education in the context of the Solar System was PlanetarySystemGO [Cos20]. This augmented reality smartphone application is based on GPS location to teach the relationships of the distances between planets using different scales, coinciding with the purpose of this paper. The objective of this work was the acquisition of general information about celestial bodies and planets orbits, for which multiple choice question sets were used to assess learning.

The application consists of a kind of search for planets in an outdoor space. Players need to walk in the real world to find virtual objects, which are celestial bodies such as stars or planets that appear on the screen of the mobile device. The arena of the game must be defined by choosing a certain scale according to the preferences of the user and the outdoor space available for walking in the real world. The application will use its location in the real world (collected by GPS coordinates) which will be the location of the star of the Solar System in the virtual world and the limit of the arena will correspond to the orbital radius of the last planet. Users earn points as they successfully find the orbits of the planets and the celestial bodies, or also answering the questions correctly. In this way, they will learn data about the planets and perform a realistic comparison of the distances between planets as they move through real space.

4. DISCUSSION

4.1 Design base of graphical interface

Starting with the definition of basic interactions, it is taken into account that children will handle the application on a touch screen, and in a short space of time. Mobile Science Center will be made up of several stations through which children will pass, one after another. Due to these characteristics, interactions must be simple and intuitive so as not to waste time understanding how the application works. To do this, they will interact with widgets such as buttons that the user will tap with a finger to choose options and advance with the learning content. To clarify this operation, the graphical interface will have icons to exemplify its use, as well as textual indications.

As it has proven to be very useful for STEM education, storytelling is introduced in all Mobile Science Center applications. The story puts the user in the role of a Polish astronaut who has to take off in a spacecraft to carry out various missions in space. Each application is a different mission that they must complete, and for which they need some spatial knowledge to do it successfully. In this way, their actions are related to real knowledge, so that children get an idea of the importance of astronomy. Narrative guides them through the applications using dialogues between the protagonist astronaut and the workers of the Polish Space Agency. They explain the details of the mission, the problem to be solved and the knowledge that users must learn. In addition, the applications give feedback in the form of points depending on how they perform the actions or the sooner they get the questions right.

Because of the target audience, the graphical interface that represents interactions and narrative will have an artistic style aimed at children, also including spatial motifs. Dialogues, in addition to being narrated by audio, will be displayed in the form of subtitles. Interactions with the touch screen and all feedback the users receive will also be accompanied by different audio effects and visual icons to identify them. In the event that the user shows difficulties in completing the space missions, each application will give him textual advice or clues so that they can solve them and fulfill the education goal.

4.2 Design of astronomy scale representations

From astronomy previous works, certain educational keys can be obtained to transmit the relationship of spatial proportions and distances:

- Assimilate the tools of the cartographic framework, a subject that is taught since primary school and that is widely disseminated [Ged17].
- Need for comparison and reference points to interpret distances and sizes [Ged17].
- Relate the distance between two points with the speed of an agent in motion and the time that this displacement takes [Ged17].

- Use reference points of the real space in which the user lives to understand the relationship between large distances [Cos20].

Based on these points, this paper develops a graphical scale to explain the distance between celestial objects in the applications. Distances shown range from Hohmann's transfer orbit change, to the Solar System, to the Milky Way and other constellations. The user discovers them and interacts with the celestial bodies as if traveling in a spacecraft. The challenge is how to reflect the proportional distances in the trips so that the children can assimilate this astronomical knowledge.

The starting point on which the application is based is the relation of the distance between celestial objects with the speed of the spacecraft and the time it takes. The spacecraft travels at the speed of light (299,792,458 m/s) to establish a measure that users have as a basis. Still, the speed of light is somewhat too fast for human interpretation, so the next step is to equalize the spacecraft's trips with the distance of a person walks in the same time. For example, it takes 8.3 minutes for the light from the Sun to reach Earth, as does a person walks about 830 meters. Therefore, the distance of the Earth from the Sun (AU) corresponds to 830 meters on the applications scale. In this way, space travel is compared with the day-to-day movements of a person in their real space to understand the proportions.

To explain the distance between celestial bodies not only by numbers, since it could be confusing for children, the cartography scales will be applied. Numerous studies have indicated that spatial thinking and numerical reasoning are closely related. Furthermore, children seem to use analog mental transformation strategies for spatial scaling [Mix12, New15]. Therefore, the understanding of scale relations is similar to proportional equivalence. This means that users can understand that the distances displayed in different sizes within the application correspond to the proportions of the real world [Möh18].

Therefore, this project develops a linear scale from the base measure of the distance that light travels for 1 minute and which is equivalent to the 100 meters that a person walks. This value has smaller units created for travel between orbits and larger units for the Solar System and stars. The relationship between these units will follow a decimal system as can be seen in Table 1. There are 2 lower units that are equivalent to 0.1 minutes (6 seconds) and 10 meters traveled, and 0.01 minutes (0,6 seconds) and 1 meter distance. For the higher units, the next step is 10 minutes and 1 km of distance and, the third measure corresponds to 100 minutes of travel of light and 10 km of distance traveled by a person.

Those measurements will be enough for the Solar System, but the trip between stars will need greater distances. Therefore, for Milky Way and Constellations applications, the base measurement of the speed of light in 1 min and 100 meters will become 1 light year and 10 billion (10^{12}) km. In addition, a higher unit is added that is equivalent to a thousand light years and 10,000 billion km. Although the use of a logarithmic scale was considered, the idea was discarded due to the added difficulty for the target audience of this application. There are studies that show the importance of children's familiarity with numbers and the decimal system when creating calculation patterns [Moe09]. Consequently, from the age of 7 they should have no problems understanding this scale [Möh18].

Orbits and Solar System		**Color**	**Milky Way and Constellations**	
Time unit [min]	**Distance [m]**		**Time unit [l.y.]**	**Distance [billion of km]**
0.01	1	Red	0.01	0.1
0.1	10	Orange	0.1	1
1	100	Yellow	1	10
10	1,000	Green	10	100
100	10,000	Blue	100	1,000
		Violet	1000	10,000

Table 1. Astronomy scale units of this project

4.3 Graphical proposals for this project

To graphically represent the proposed scale, shapes and geometric objects are used, with relationships between them. Besides, proposals in a two-dimensional or a three-dimensional representation are offered. The interface follows psychology of color principles to help distinguish the closest or farthest distances. The 2D images of the interface have the ability to generate different visual signals according to the differences in size, contrast, luminance and/or color [von15]. When objects have the same contrast, shape and size, warm colors make the observer think that they are closer than cold colors [Egu83]. To represent these scales, the interface also needs uniform backgrounds to improve color stability and related perceptions [Dre20]. In addition, the order in which these elements appear when they are grouped also influences. The object with the lowest position in the plane will have an even greater probability of appearing closer to the human observer [Gui04].

There are 4 proposals which are explained below and shown in Figure 2:

1. Each unit of the scale is represented in 2D with a bar and the color that has been assigned to it.

Each bar has the same length even if the decimal system between them is maintained. The bars are ordered by rows, those of smaller units in the lower ones and the larger units in the upper ones.

2. Smaller units of the scale are represented in 2D and as they increase in the decimal system their composition increases until the last unit is represented in 3D. Each unit is represented by a geometric shape that forms when the next unit is joined. The progression is: point, line, bar, rectangle, square, and cuboid.

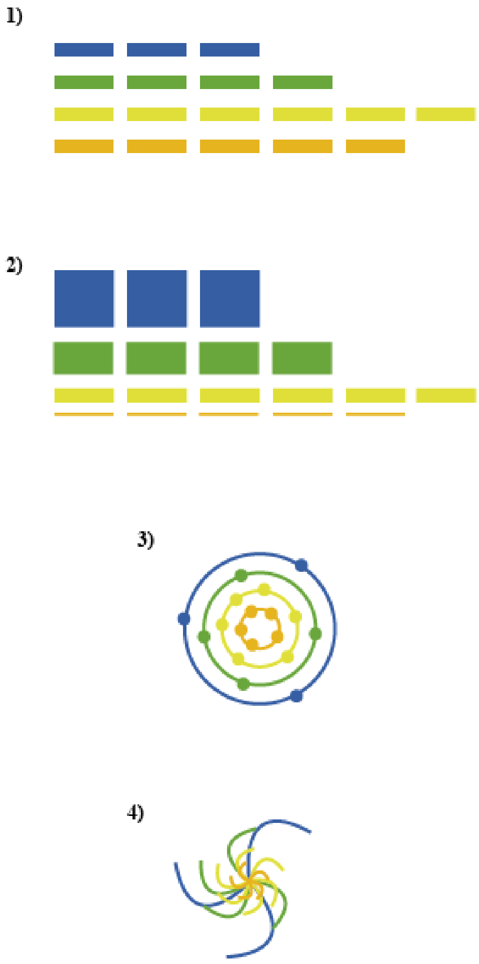


Figure 2. Example of the 4 proposals representing 346.5 light years

3. Each unit of the scale is represented in 2D in the form of concentric circles, the larger units are the outer circles and the smaller units are the inner ones. To represent the number of units that form the distance, each circumference will have the same number of points on it. This representation is proposed because it reminds the icons that are used for planets and their orbits.
4. Each unit of the scale is represented in 2D as a set of spiral lines coming from the same point. The larger units have longer lines and the smaller units have shorter lines. To represent the number of units that form the distance, a line is drawn for each one. This representation is proposed because it reminds the icons that are used for galaxies.

Following psychology of color principles, the smallest step of the scale uses a warm color, red, while it cool downs changing to orange and yellow, green and blue in the middle, and violet in the largest. The chosen colors have the same luminance value with the same background to maintain the contrast and sensation of distance. This relationship of the scale with the necessary time and the equivalence of the distance is explained through the astronaut's dialogues and the explanation of the mission. In each application, users are asked to travel from one celestial body to another that is at a distance. The distance is graphically represented in the interface and the user has to calculate the exact distance that is asked, with the decimal system of the scale always visible to check. For color blind participants, the graphic representations will be accompanied by signs with which they will be able to identify them. An answer is chosen from 3 possible options and the user gets more points doing it right on the first try. Table 2 shows an example of proposal 1 representation of distances from the Sun to the rest of the planets that applies to the Solar System application.

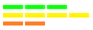
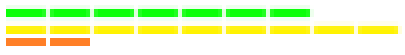
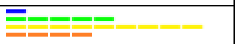
Planet	**Time [min]**	**Reference distance [m]**	**Scale representation**
Mercury	3.2	320	
Venus	6.0	600	
Earth	8.3	830	
Mars	12.4	1,240	
Jupiter	34.2	3,420	
Saturn	79.2	7,920	
Uranus	159.4	15,940	
Neptune	250.0	25,000	

Table 2. Relations of time, distance and scale representation from the Sun to every planet

In addition to this scale and graphic representation, since Mobile Science Center will travel to different cities, the representation will be customized for those citizens. While showing the relative distances between space objects, the applications will also show a real map of the city for short distances and an Earth map for long distances. A representative building of the city will be chosen to place the origin position of the spacecraft and hence the position of the celestial objects following the scale. For example, the users will visualize that the store 320 meters from the building would be equivalent to the displacement from Sun to Mercury, but to go to Neptune they would have to travel 25 km to the nearby town. For the routes within Milky Way and Constellations, the Earth map will be used to simulate the equivalence of distances.

These applications are meant to run one after another in a short space of time. Therefore, when rendering the animations of the spacecraft's journeys it is not possible to take minutes. In order for the scales and the required time to be understood as such, it is necessary to introduce another animation. A clock is included for short trips and a calendar for long trips. In this way, although the animations only take a few seconds, which will be proportional in each one, users will see the passage of time in the change of times and dates.

5. CONCLUSION

This paper has obtained a framework to develop a graphical interface for astronomy applications with educational goals. It has focused on the visual representation of spatial proportions and distances with the aim that children understand them. This framework is used on touch devices that offer easy interaction. Learning is guided by storytelling that introduces the educational content and the actions that the user must perform. The challenges have to be regulated in difficulty and accessibility, always giving feedback through sound and visual elements. Previous works have also highlighted the importance of using shapes and geometric objects, cartographic tools, reference points and comparison with known velocities and spaces.

Applications designed for this project’s Mobile Science Center include the narrative of an astronaut conducting space missions to introduce learning. The representation of spatial proportions occurs when the astronaut travels in a spacecraft from one celestial body to another. The distances are represented following a decimal system scale that compares traveling at the speed of light with a person walking. These measurements are counted by minutes and meters at distances within orbits and the Solar System, and light years and billions of km within Milky Way and constellations. In the graphic representation, each unit of the scale has a color and position assigned according to its proximity or distance. Four proposals are made to represent the units with different geometric shapes and interrelated structures. The applications also offer animations showing elapsed travel time and personalized comparisons of distance traveled.

The framework and the 4 graphical proposals developed in this paper will be programmed and introduced in the current prototypes of the Mobile Science Center. Once its correct functioning is verified, tests will be carried out with children to verify their satisfaction with all the characteristics described. Motivation, ease of use and level of learning will be measured, being especially relevant the division into groups that manage the different proposals. In this way it will be possible to identify which representation of the graphical interface is more useful for learning spatial distances. Finally, the proposal identified will be implemented in the final version of the applications.

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