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Q3D-Game: A Tool for Training Users' 3D Spatial Skills

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Abstract. This paper presents a computer game developed to apply the qualitative model for describing 3D objects (Q3D) using depth and different perspectives. The Q3D-Game shows how to build objects out of cubes; and how the top, front and lateral views of an object can be extracted. It also explains the differences in depth in each perspective and relates them to the Q3D model. This knowledge is acquired by the system enabling it to infer perspective features of 3D objects by consistency checking. The Q3D-Game also motivates users while playing so that they train and improve their spatial abilities. These abilities are trained using tasks such as 3D object block building and answering questions from the Perceptual Ability Test (PAT, part IV) which measure intelligence in humans. The Q3D-Game testing process by humans is currently in progress.

Keywords. qualitative descriptors, logics, spatial skills, spatial cognition, computer games, education, consistency

1. Introduction

Qualitative Spatial and Temporal Representations and Reasoning (QSTR) [1,2] models and reasons about *time* (i.e. coincidence, order, concurrency, overlap, granularity) and also about properties of *space* (i.e. topology, location, direction, proximity, geometry, intersection, etc.) and their evolution between continuous neighbouring situations. Maintaining the consistency in space and time are the basics in qualitative reasoning when solving spatial and temporal problems. Spatio-temporal reasoning models deal with imprecise and incomplete knowledge on a symbolic level and have been successful in many areas and applications such as robotics [3], computer vision [4], ambient intelligence [5], colour analysis of artistic paintings [6], classification of volunteered geographic information [7], etc. Furthermore, qualitative representations are thought to be closer to the cognitive domain, as showed by models for object sketch recognition [8], map sketch understanding [9] and spatial problem solving tasks [10].

In the field of psychology, spatial cognition studies have shown that there is a strong link between success in Science, Technology, Engineering and Math (STEM) disciplines and spatial abilities [11,12]. Spatial abilities are fundamental for very relevant job skills, such as visualizing the result of a surgery, designing bridges, aircrafts; interpreting charts,

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maps, diagrams, engineering drawings, etc. Moreover, it appears that 3D spatial skills can be developed through practice [13] since research has showed that students that attended an engineering graphics gateway course at university to improve their ability to visualize in three dimensions, improved their success and retention significantly, particularly female students. Thus, it is important to maintain and train these abilities from the early stages, which will also have a beneficial impact on gender equality. For this reason, researchers in US and Canada study the actualities of training spatial reasoning also in contemporary school mathematics [14].

In cognitive psychology, games like *Upside Down World* are used to evaluate students' spatial skills when they are challenged to recreate buildings composed of multilink cubes and use spatial language in order to describe the composition of these buildings, so that their colleagues can build them accordingly [14]. Spatial learning and reasoning can also be taught using visual and kinetic interactions offered by new digital technologies [15]. Research has demonstrated that video game training enhances cognitive control [16] specially when aging [17]. Although there are computer games on wayfinding which require spatial cognitive skills at a more *large-scale* [18,19], most studies of the relationship between spatial skills and video games have focused on *small-scale* spatial abilities (i.e. experiments on mental rotation, embedded figures, perspective taking, paper folding, form boards, and block design).

Some successful computer games in the literature that are related to this paper and inspired our work are: (i) Sea Hero Quest[2] which gets data on players' spatial navigation skills and it is aimed to help researchers to find out what is wrong with navigation skills in patients with Alzheimer and dementia; (ii) Minecraft[3], which allows users to play with 3D cubes to build objects; and (iii) Robologic[4], which uses 3D cubes to teach programming to kids. However, Minecraft and Robologic were not designed to train spatial cognition skills, and none of those three games were developed to help players' to solve perceptual ability tests (PAT), as Q3D-Game does using Q3D.

Qualitative models that try to solve spatial games have appeared in the literature. A qualitative descriptor for solving paper folding tests [20] was defined by establishing a correspondence between the possible folding actions and the areas in the paper where a hole can be punched [21]. A logic-based formalization of the Fishermans Folly puzzle was proposed using qualitative spatial reasoning about non-trivial physical objects (such as strings and holes) and reasoning about actions and change on these objects [22]. A qualitative model for describing 3D objects (Q3D) using depth and different perspectives [23] was defined to help users to solve perceptual ability tests.

This paper presents a new tool to train visualization and description of 3D objects. Q3D-game is a computer game that shows how to build objects out of cubes; teaches how the top, front and lateral views of an object are extracted; shows the differences in depth in each perspective and relates them to the Q3D model. The Q3D-Game also presents a perceptual ability test and it motivates users while playing in order to train their spatial abilities. The rest of the paper is organised as follows. Section 2 outlines the challenges of perceptual ability tests carried out using pencil and paper. Section 3 presents a model for Qualitative Description of 3D objects. Section 4 describes the Q3D-game and its implementation. And conclusions and future work are presented in Section 5.

[2]Sea Hero Quest: http://www.seaheroquest.com/de/credits

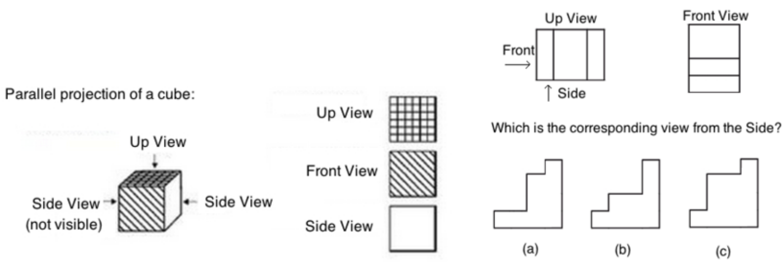
[3]Minecraft: https://minecraft.net/en/

[4]Robologic in iTunes: https://itunes.apple.com/us/app/robo-logic/id300025550?mt=8

2. Outlining the Challenges of Pencil-and-Paper 3D Perceptual Ability Tests

Pencil-and-paper 3D perceptual ability tests are used by: (i) the German Academic Foundation to measure intelligence in students[5] by asking them for the consistent view/projection of a 3D object corresponding to a technological drawing; and by (ii) the north American Dental Association which includes a Perceptual Ability Test (PAT) in its Dental Admission Testing Program[6] for selecting dental students [24].

An example of a question in this kind of tests and the instructions given may be that provided[7] in Figure 1. Note that, in PAT questions (see Figure 1) views are provided



(a) Intructions provided to participants (b) Example of a question

Figure 1. (a) Intructions of the test; and (b) example of a question regarding 3D perspectives included in the German Academic Foundation test or in the PAT.

disconnected from each other, whereas in 3D technological drawings, engineers assume **continuity** in their abstractions or re-representations. When assuming a constant value for a dimension, it is assumed also that this dimension is continuous. If a change is produced in the dimension abstracted, this change has to be reflected in the other representations. In order to reflect this continuity in the description of 3D objects, a qualitative model based on depths was formulated [6] and it is outlined in next section.

3. A Qualitative Descriptor for 3D Objects (Q3D)

Q3D descriptor is based on the levels of depth a 3D object has at each perspective. This approach is inspired in designs which abstract the main features of an object from all their properties in the real world and describe them using 3 canonical views (top, lateral and front). This approach is cognitively based, since experimental psychology supports for the idea that human object recognition involves view-dependent representations, that is, people prefer to imagine/view/photograph objects from certain canonical views [25].

The reference system for a qualitative 3D object descriptor [23] is defined as follows:

$$Q3D_{RS} = \{F, R, U \in P \mid P \subseteq N_{depths}\} \;\; N_{depths} = \{a, b, c, d, \cdots, *\}$$

[5] *Test der Studienstiftung: Gehirnjogging für Hochbegabte*, see Spiegel Online: `http://www.spiegel.de/quiztool/quiztool-49771.html`

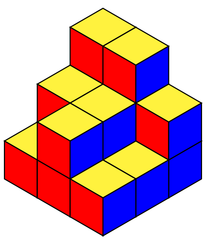
[6] *Dental Admission Testing Program example*: `http://www.ada.org/`

[7] Note that this example is made up for this paper to avoid copyright issues, and that real examples can be obtained online.

where F, R and U are the Front, Right and Up perspectives (P) or views of the object, and N is the total number of cubes which compose each edge of the object. That is, the edges of the object in each perspective are described by the volume of cubes of equal size, being the basic unit of measure considered a cube of side $x \in \mathbb{R}$ (i.e., $x = 1$cm, $x = 0.75$cm, $x = 5$m, etc.).

Thus, each perspective has N levels of depth, which can be named differently and sequentially as $\{a, b, c, d, \cdots, *\}$ where a is the surface of the cube, b is the first level of depth (a previous cube in the row has been removed), c is the second level of depth (two previous cubes in the row have been removed) and so on, until $*$ is reached, which indicates that all the cubes in a row have been removed. The description is started from the upper-left part at each perspective.

As a first example, let us consider the object in Figure 2 and its corresponding description according to the views: Front (F) in red, Right (R) in blue, and Up (U) in yellow. Starting from the *front* perspective, note that at the basis of the object, all the rows



Front	Right	Up
$[c, c, *]$	$[*, *, b]$	$[a, a, b]$
$[b, a, c]$	$[b, b, a]$	$[b, b, c]$
$[a, a, a]$	$[a, a, a]$	$[c, b, c]$

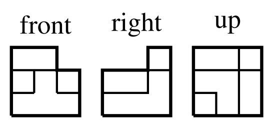


Figure 2. Example of 3D object divided by a 3*x*3*x*3 grid of cubes showing the front (red), right (blue) and up (yellow) views, its Q3D description and its corresponding drawing sketch.

are complete, which is represented as *a,a,a* in the Q3D description. Going up a level, it can be observed that only one cube was removed in the first row (represented by b), then the second row is completely filled (represented as a) and, in the third row, two cubes are missing (represented as c). Finally, in the upper-left part of the *front* perspective, it can be observed that 2 cubes were removed in the first and second row, which is represented by the parameters *c,c*, and that all the cubes were removed in the third row, which is represented by the parameter $*$. The *right* and *up* perspectives are explained similarly.

It is important to notice that a change in a parameter in the Q3D description (i.e. from a to b) corresponds to a line of the engineering sketch drawing (see Figure 2). And that the parameter $*$ corresponds to open spaces which can have open boundaries. Therefore, some hints about the **shape** of the object are obtained.

The Q3D has **consistency** properties based on the continuity of space that must be fulfilled. If a cube is removed at one of the edges of the object –that is, where 2 views are coinciding–, this change, in order to be consistent, must be transmitted to the other views. For example, the b depth parameter in the front view, indicates that one cube disappeared in the front perspective so, from the left perspective, it cannot appear an a describing the same place, the given possibilities are: b, c, or $*$. More details are given in [23].

According to the properties of continuity and relativity of spatial substrates, some features of the views that are not seen can be **inferred** by taking into account:

– *Hole Continuity:* all the holes observed in a view affect the opposite views of the object, that is, front-back, right-left, up-down.

– *Depth Relativity:* features indicating the last level of depth in a view (i.e., level c in a $3x3x3$ description), involve the existence of the first level of depth in the opposite view (always level a). Taking into account this property, the following features could be inferred regarding the *back*, *left* and *down* views of object 1:

Back	Left	Down
$[*,a,a]$	$[\_,*,*]$	$[\_,\_,\_]$
$[a,\_,\_]$	$[\_,\_,\_]$	$[a,\_,\_]$
$[\_,\_,\_]$	$[\_,\_,\_]$	$[a,\_,a]$

Following these logics, the Q3D model proved its performance when implemented in Horn clauses using Swi-Prolog platform [26].

4. Q3D-Game

Research has demonstrated that realistic 3D views enhanced users' performance on spatial visualization tests [27] and that 3D spatial skills can be developed through practice [13]. Thus, an interactive application, Q3D-Game, which shows realistic 3D views of objects, was created for testing the Q3D model. The Q3D-Game playing possibilities are described in Section 4.1 and details about its implementation are provided in Section 4.2.

4.1. Q3D-Game Description

The Q3D-Game has three different playing options: (i) object building, (ii) object description, and (iii) perspective question answering. This gameplay is described next:

– *Object building*, where players learn how to build objects using cubes by reproducing several object models. They can add a cube by touching a cube face and they can remove a cube by throwing it away (i.e. a long continuous movement). This is how the gameplay starts and the players can keep building up to 8 different objects.

– *Object description*, where players are shown how to describe an object from its perspectives, using the traditional third angle orthographic projection, and adding the Q3D description to provide information about depth. This is explained interactively using the built objects. Training examples are given to the players so that they can use the Q3D model to describe their perspectives (Figure 3). Two assisting hints are given during the

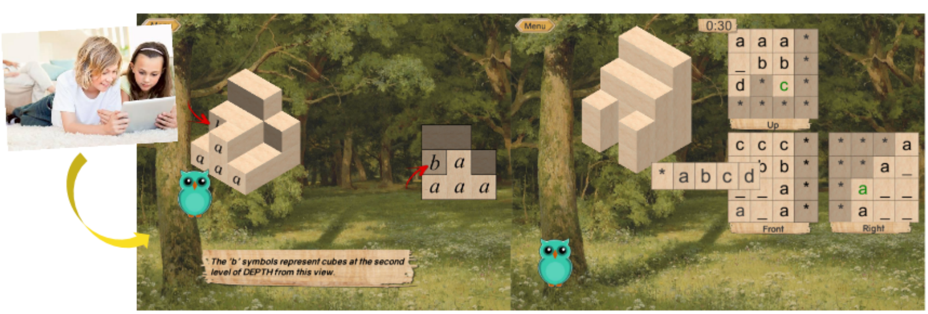


Figure 3. Q3D-Game snapshots: (i) Object building and (ii) providing the Q3D

description process: (i) automatically providing the hole values ('*') to the player as a hint to better understand the object; and, (ii) providing some depths automatically when a parameter is given by the player, according to the consistency rules defined in the Q3D model. When a new depth is typed in a view, the corresponding depths in the other two views are inferred. In this part, 8 objects are also used. For the 1^{st} and 2^{nd} objects, both hints are given; for the 3^{rd} and 4^{th} objects, only the hole values are given; for the 5^{th} and 6^{th} objects, only the automatic depth obtained from the consistency rules is given; and finally, for the 7^{th} and 8^{th} objects, players must complete the Q3D description with no help options.

– *Perspective question answering*, where players are asked questions of the Perceptual Ability Test (PAT, part IV, similar to that shown in Figure 1), that is, they are given 2 views of an object and four possibilities of the third view are provided as options (Figure 4). Participants can solve the question directly or they can ask for help using two options: (i) visualizing a grid, which draws on the object all the cube edges and facilitates cube counting; and (ii) using the Q3D description, which provides information about the level of depth of each area in the perspective. When players select an answer for the test, the

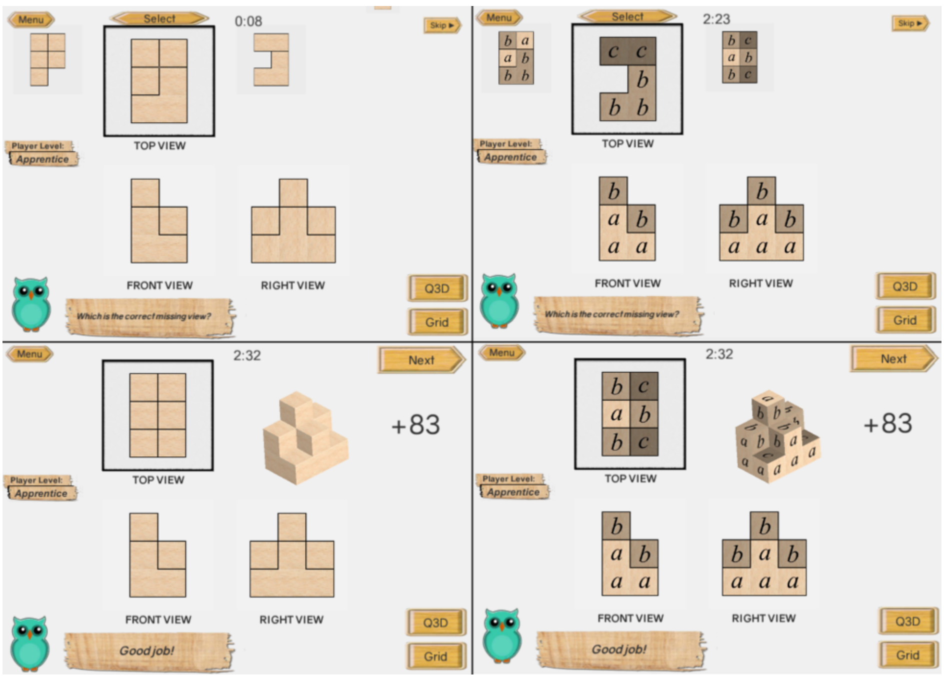


Figure 4. Perspective question answering; with and without the Q3D hint before and after answering the question.

Q3D-Game provides the correct solution and the real object is shown in 3D, so that players can turn it and see how the perspectives correspond. In this test, 20 different questions are presented in two levels of difficulty determined by the complexity of the object.

In the three game playing options, players are provided feedback with respect to their performance, as follows:

– In the object building part: players are rated based on the time it takes for them to build the object showed.

– In the object description part: players are rated based on the time they spend in providing the correct Q3D description.

– In the perspective questions part: the time used to solve each question is showed to the players and also influences the final score obtained. In this occasion, giving the correct answer is essential to obtain a score, since a wrong answer results in a score of 0. The conversion from time to score is based on an hyperbolic growth. In this way, Q3D-Game encourages players to focus on the task and solve it quickly, while it ensures any player obtains a score greater than 0, if the correct answer is provided. The conversion between time t and score s is done using the following formula: $s = \frac{500}{(t+27)/30}$. The maximum score is not greater than 500 when t is smaller than 3s.

4.2. Q3D-Game Development

The Q3D-Game runs on any tablet/mobile with an operative system Android 2.3.1 'Gingerbread' (API level 9) or upper version. The game engine used was Unity[8] 5 because it provides multiplatform exporting, allowing to easily release a version for Android mobiles and tablets. Unity game engine provides different tools useful for application development, such as: (i) 2D and 3D graphic creation engine; (ii) input management for computer and touch devices; (iii) custom shading; (iv) scripting in C#; etc. Figure 5 presents a diagram to show how the Q3D-Game options have been implemented.

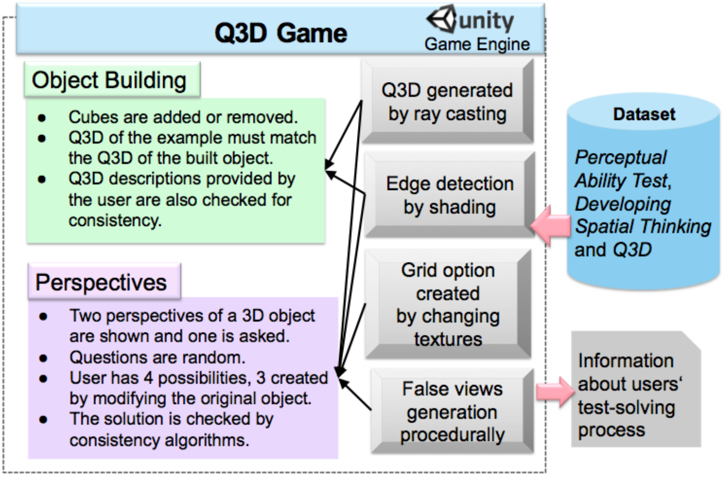


Figure 5. Q3D-Game options and the main implementation procedures.

In the Q3D-Game *object building option*, players are asked to build objects using cubes interactively using the tablet touch screen. Thus, the touch input of the user on the Android system is captured. Then, the screen pixel coordinates are translated into world coordinates using *raycasting* to detect where the player is pressing and to add a cube in the correct position.

[8]Unity game engine: `http://unity3d.com`

The *edge detection* approach applied in the Q3D-Game to draw the lines that define object edges in each perspective uses the *edge detect normals color shader*[9] available on Unity platform. The shader is tuned by finding differential depths that surpass a given threshold on an object to be able to detect the edges and highlight those pixels in black.

The *grid help option* is composed by grey lines that cover the edges of each cube. This effect is obtained by changing the texture of each cube face with a similar texture that has the edges highlighted in grey. In this way, each face of the cubes displays a surrounding frame giving as a result a grid that differentiates each cube within the object.

The Q3D obtained for the displayed objects in the game is calculated by *raycasting* on the object from each perspective. The measured distance to each detected cube is then used to calculate the depth on that view. Then, this distance is translated into a depth symbol relative to the object volume in this view. The albedo[10] of the respective cube faces changes from lighter to darker colors depending on their depth. In this way, a more realistic representation of the object is showed which simulates shadowed object faces.

When the player is asked to provide the Q3D description of an object, an interactive interface is dynamically generated. This interface consists on buttons that, when pressed, they display an emergent interface with possible depth option letters (a, b, c, etc.). These depth options are adapted to the volume of the object, and when the consistency aid is given, these options are also adapted to other depth parameters already provided in related perspectives.

In the Q3D-Game *perspective questions option*, the built objects are used to generate the real 3^{rd} angle orthographic projection of the object and then 3 fake views are procedurally generated for each question. A fake view is generated by cloning the original object and applying a serial of operations that modify the object topology. These operations are:

– Perforate, that is, deleting a whole row of cubes in-depth relative to the asked view.

– Cut, that is, removing a whole plane perpendicular to the view plane, prioritizing external planes.

– Add Row, that is, adding a row of cubes of a random length. This is opposed to the *Perforate* operation.

These operations are applied semi-randomly to the different objects. After each set of operations, a recursive algorithm ensures that no *floating cubes* have been left on the object, meaning that the remaining cubes share faces, since sharing only an edge can divide the object in two. After all changes, the program checks that the new object is unique in relation to the other existing objects.

Apart from training players' spatial abilities, the role of Q3D-Game is also analyzing players' performance in order to study if the Q3D helped them to solve the PAT questions and if they improved their spatial abilities during the play, or not. For that, the following Android utilities are used to store data in a repository: (i) reading the tablet/phone status and identity; (ii) modifying or removing the contents of the USB storage; and (iii) having full network access. The data collected includes: (i) gameplay data (i.e. time to answer a question, if it was correctly answered or not, if the Q3D or the grid were used as help options, scored obtained by the player), (ii) data to categorize the player (i.e. gender, age

[9] Edge Detect Normals Color shader by *pmurph03*: `http://forum.unity3d.com/threads/image-effect-edge-detect-normals-colours-rel.310280/`

[10] Albedo is defined as a shortwave reflection coefficient. It is the ratio of reflected radiation from the surface to incident radiation upon it. In Unreal Engine, the Albedo parameter controls the base color of a surface.

and level of studies) and (iii) the opinion of the player regarding the Q3D-Game: how fun, educational, intuitive and easy-to-use it was. The Q3D-Game[11] testing process is currently in progress, any feedback for our pilot-study is very welcome!

5. Conclusions and Future Work

Spatial skills are strongly related to success in Science, Technology, Engineering and Math (STEM) disciplines and they are fundamental for relevant jobs, such as surgery, industrial engineering, aeronautics, economics, etc. 3D spatial skills can be developed through practice and video game training has been shown to enhance cognitive control, specially when aging. For all those reasons, Q3D-Game was created, that is, to train and improve players 3D spatial skills to solve Perceptual Ability Tests (PAT).

The Q3D-Game shows how to build objects out of cubes; and how the top, front and lateral views of an object can be extracted. It also explains the differences in depth in each perspective and relates them to the qualitative descriptor of 3D objects (Q3D)[23] by showing the dependencies and relativity in space. The Q3D-Game motivates users while playing in order to train their spatial abilities. These abilities are practiced using tasks such as 3D object building and answering questions from the Perceptual Ability Test (PAT, part IV) which measure intelligence in humans.

The Q3D-Game also stores data related to the performance of the users, so that a psychological study can be carried out later using this game. The Q3D-Game is available for download and for testing. A testing survey on participants is currently in progress.

As future work, we intend to analyse if the Q3D helped the players to solve the PAT questions and if they improved their spatial abilities during the play, or not. Moreover, we also intend to apply the Q3D logics to robot object perception, so that the important information can be distinguished from impossible-noisy data.

Acknowledgments

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[11] Download Q3D-Game: `https://www.dropbox.com/s/l3xs5hjwoaga9q5/Q3DGame.apk?dl=0`

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