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Supporting the Development of Spatial Orientation Skills of Blind People Using Binaural Sounds in VSR Game

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Abstract. Spatial orientation skills are crucial for the comfortable everyday functioning of blind individuals and affect their physical and mental well-being. Developing spatial orientation is usually carried out through traditional training courses without the support of electronic tools. Training them in a natural city environment, even under the supervision of an instructor, is often a very stressful process for the student. This paper proposes a solution for a simplified city space simulator created as a game using 3-dimensional binaural sounds. This simulator can be used at home to develop basic spatial orientation skills for blind people. While feedback from testing by three blind users was positive, the limited scope of this initial evaluation underscores the need for developing more advanced applications supporting the teaching of spatial orientation to blind users.

Keywords: Blind users, Binaural sounds, Virtual Sound Reality, Spatial orientation.

1 Introduction

Vision is one of the most important senses of the human body, playing a vital role in an individual's everyday functioning. Therefore, blind or partially sighted persons face many challenges that are difficult for sighted persons to imagine. One of the problems they have to work on is the limited ability to move independently in open areas[11]. For such independent movement to be possible, they must acquire many skills related to spatial orientation. When moving to an unknown place, they must rely mainly on auditory and tactile stimuli to reach the destination and avoid potential obstacles. In order to acquire these skills, dedicated mobility and spatial orientation courses are organized for them. They aim to teach them techniques for using the remaining senses, the so-called sensory substitution [13], for outside and indoor navigation. They have to involve learning to recognize the environment, determine directions, and plan travel routes. However, participating in such courses and independently navigating the city after they are finished can be very stressful. Therefore, a good solution is supporting this activity with various simulators and games to help develop and train spatial orientation skills in a much less stressful home environment. Moreover, many blind people have better-trained abilities to perceive their surroundings using hearing than sighted people. Some can hear sounds reaching them and recognize their direction and intensity. However, they can also recognize sounds reflected from large-sized obstacles such as building walls or even cars standing on the sidewalk. For some time, this phenomenon was considered an additional sense possessed by blind people, was researched at the end of the 20th century [19], and is called echolocation. With the development of modern technology, it has become possible to simulate the sound environment using computer technologies such as binaural sounds. Binaural sound is stereo audio that is recorded through a dual microphone setup [26]. Recording binaural sound aims to create a 3D audio effect that simulates sound as if it is being heard live. Binaural beats are used in virtual and augmented reality games to elicit the player's autonomic sensory meridian response (ASMR). Such binaural sounds may be generated automatically, i.e., using HRTF Filter, or recorded on four stereo channels and played back in the user's headphones, giving him an acoustic view of the surrounding space.

Since describing the space regarding a user's specific needs, such as a blind person, is not simple, using a simple ontology seems to be a good solution. Taking up this challenge, we propose a combination of a simplified ontology and binaural sounds to support the process of training the spatial orientation skills of blind individuals. A practical implementation of this issue is a game developed in the Unity environment using a simple user interface and binaural sound scenes. The mechanism of its operation is based on the player's interaction with the application using the keyboard, allowing him to move around the virtual city to collect coins. During the game, the participant must avoid moving vehicles and other potential threats. The critical element of the game is the coins. The game ends when all the coins are collected, and the player's score is saved in a database, allowing them to track their achievements. The application, which is the first practical step in developing this idea, was tested by three blind users. They gave positive feedback and suggested some improvements and changes.

The rest of the work has the following structure. In the next section, we will present solutions that support the spatial orientation of blind people. Then, we will present the concept of the proposed solution, i.e., works. Binaural sounds and the simple ontology used.

In the following section, we will provide some details about the practical operation of the implemented application. We will end with a summary and plans for the future.

2 Technological background and related solutions

Many tools and technologies significantly facilitate navigation and spatial orientation for blind people. Traditional methods include white canes and guide dogs, However, these methods only sometimes provide all relevant environmental information. A blind person often has to rely on information from sighted people around them, such as asking for guidance through a complicated intersection or reading the number of a bus that is currently arriving at the stop.

Fortunately, in recent years, many modern electronic solutions have appeared that significantly expand the independence of blind people in terms of spatial orientation. To facilitate city navigation, blind and partially sighted users can use various programs on their mobile devices that use GPS satellite systems. Today's mobile operating systems have accessibility functions, so every user can run software on their phone that reads information from the screen using synthetic speech. For example, in Android systems, it is ”Talkback” software [24], while for IOS systems, there is a ”VoiceOver” [5]. With these facilities, a user can use standard software installed on his phone just like a sighted person; however, it can be done slightly differently, i.e., using a different set of gestures.

An example of a dedicated solution supporting outdoor navigation is ”Seeing Assistant Move” [21]. It helps search for a destination address and lists nearby points of interest, such as intersections, shops, etc. The program automatically guides the user to the selected point, records the route, and responds to voice commands. The application is available for both Android and iOS systems.

Another helpful tool for blind users is ”DotWalker” software [6]. It is a travel assistance application intended mainly for visually impaired people. The application allows the user to set landmarks on the map and informs him /her about the direction he/she needs to take and the distance he/she needs to cover. Each landmark can be assigned an audio recording, text file, or website URL. The application can be installed on Android devices.

A solution similar to ”DotWalker” is the ”Lazarillo” program [12]. It is a navigation application for people with disabilities that allows them to explore the area safely using voice prompts. While walking, the program informs users about upcoming places worth visiting, such as street intersections, restaurants, and shops. ”Lazarillo” also allows users to create routes to specific locations, browse nearby locations by category, and search for specific places. He/she can also save his/her favourite locations for easy access anytime. It is available in over twenty languages and is compatible with Android and iOS platforms.

Supporting navigation inside buildings is a bigger problem than outside navigation because GPS-based tools are unavailable. These tools can be divided into two main categories:

- Locating devices - These include advanced technologies that precisely determine the user's Location. An example of such a tool is ”NaviEye” [7].
- Devices that detect obstacles on the road - These are technologies that identify obstacles in the surroundings. They scan the area using various sensors and cameras and warn the user about potential road hazards. An example of such technology is the application ”Obstacle Detector” – [18] For blind people.

Locating devices helps the user determine the direction in which to move.

One of the few solutions supporting navigation inside buildings is the ”NavCog” system. It is a navigation assistant for smartphones designed to enable blind people to navigate in unfamiliar environments. The system uses a network of beacons, i.e., Bluetooth low energy (BLE) transmitters, to locate the user using an approach based on the K-nearest neighbours (KNN) algorithm [20]. ”NavCog” guides the user through the surroundings and signals the presence of nearby points of interest, such as doors, shops, etc.

A solution similar to ”NavCog” is the ”NaviSecure” application [17]. The ”NaviSecure” system supports the navigation and safety of students and employees on the academic campus. Like ”NavCog,” it is based on an infrastructure of Bluetooth low-energy (BLE) transmitters and a map expressed in a dedicated ontology. However, unlike ”NavCog”, it supports not only blind people but also people with other disabilities and can be used by all users.

Although several tools exist that help blind users navigate, the topic of supporting the teaching of spatial orientation has not been developed. The authors of the work [3] pointed out that moving independently is stressful for blind people, even experienced people, and especially for beginners in the art of spatial orientation. They investigated that blind people plan their routes and use various strategies to avoid constantly asking passers-by for help. They also try to cover as few pedestrian crossings and other places that could cause them problems as possible. Authors of the work [2] noticed that using audio games to develop the ability to explore spaces for blind people is a good solution. They proposed and researched a game that uses 3-dimensional sounds intended to develop the spatial perception skills of a blind user.

Very few works address the topic of supporting the navigation of blind people using virtual reality using binaural sounds. One example would be paper [8], in which authors constructed a simple electronic travel aid based on an infrared laser pulse and measured the time of flight distance between the user and equipment. They noticed that blind people localize sounds more accurately than sighted people using monaural and/or binaural cues.

In the work [1], The authors propose combining binaural sounds with bone headphones to support the navigation of a blind user. The authors used sounds generated using the Head Related Transfer Function HRTF, which is similar to the solution proposed in this work. Additionally, bone headphones that are not placed on the user’s ears but rest on the temple bones allow the user to listen to sounds coming from the headphones simultaneously without disturbing them while listening to sounds from the surroundings. It is a popular way of supporting navigation applications that blind people use in open spaces. The authors tested whether using binaural sounds instead of voice messages speeds up a blind user’s ability to find a destination. The only problem in this case is that the user has to learn these binaural signals, which is easy if they are intuitive enough.

A similar system was constructed and tested by the authors of the work [4], who simultaneously used binaural sounds generated using the HRTF function and a touch interface based on vibrations. In their work, they discuss the improvement in the quality of user navigation that they observed in a group of about a dozen users after using their system. An attractive solution is also a system called stereopilot, proposed by the authors of the work [10]. It is a device used to find objects on the user’s desk. It comprises a camera and software that transforms the received image into a scene created using binaural sounds. As in the abovementioned systems, sounds are generated using the HRTF function.

As we can see, binaural sounds and their use to support navigation and the everyday life of the blind are among the latest research trends. However, supporting the teaching of spatial orientation to blind people using systems that use them has not yet been explored much. Simulation of the echolocation phenomenon using binaural sound technology also opens up a wide field for future research. Therefore, it seems that teaching spatial orientation using Virtual Sound Reality may become an up-and-coming solution [16]. This paper also covers this topic, proposing a simple game to develop these skills.

3 Virtual Sound Reality

A system based on virtual sound reality (VSR) to facilitate the training of blind people's spatial orientation skills is proposed. Generally speaking, it consists of two main components. The first is an ontology in which information about the user's environment is stored, supporting the user's virtual navigation around it. The second is a set of sound scenes recorded with binaural technology. These scenes represent the environment in a way appropriate for a blind user, replacing the visual image that a sighted user would have with 3-dimensional binaural sounds and speech messages emitted by a speech synthesizer built into the operation system. Particular elements of these scenes, such as binaural sounds and voice messages, are assigned to particular objects in the ontology.

According to the classic definition by Tom Gruber [9], ontology is a specification of a conceptualization, and every intelligent application must have such a conceptualization of the part of the world it wants to discuss. Ontology is an IT representation of a fragment of the world created to describe it so that the meaning of the concepts described in it can be automatically processed. To support the development of skills related to spatial orientation, we propose an ontology describing the city space in which a blind person is to move. Therefore, such a description must be appropriately adapted to show, on the one hand, the structure of streets, buildings, and other objects that users may encounter in the city and, on the other hand, any obstacles that may be encountered there, such as passing cars or objects on the sidewalk. This space description is presented to a blind user not in a visual form, as is the case for a sighted person, but in an audio form. Therefore, in our ontology, we must include both an object ((avatar) representing the user and sounds that are a substitute for visual scenes. These sounds are assigned to individual objects in the ontology and are made using binaural technology. It allows the user to hear them from a 3-dimensional perspective as they do in reality.

The ontology was defined in OWL [15] as a particular hierarchy of classes, properties, and data properties that represent the relationships and characteristics of individual objects. The objects themselves are represented as appropriate individuals derived from defined classes. The selected class hierarchy looks as follows. At the top of the hierarchy is the owl hing class, from which they inherit the following classes:

1. City_Components – the class represents the physical and stationary elements of the city. Further classes are derived from this class, categorizing various groups of objects in the city, such as:
   (a) Elements_Of_City_Architecture – represents typical objects users can find along the street. It derives subclasses such as Advertising Column, ATM, Boltard, Bus Stop, Pole, Road Sign, Traffic Light, and Trash Can.

(b) Infrastructure_For_Pedestrians – these elements set the route for blind people he will move on them. from this class are derived such subclasses as Lift, Pavement, Pedestrian Crossing, lights, or Stairs;
(c) Road_Infrastructure, along with sub-classes: Bridge, Cross_Roads, Street, Traffic_-Circle, and Tunnel.
(d) Location – usually every element of city architecture has its Location (address) and geo-location coordinates;
(e) Real_Estate – it can be a destination, a Point Of Interest, and other buildings along which the user moves on its way.
(f) Vehicle – the class represents moving objects, but which can be assigned a specific sound that they emit. e.g.: Bus, Car, etc.;
(g) Voice – every place on the route can be assigned a binaural sound, e.g., an MP3 or WAV format file.

OWL data properties define the data types that can be assigned to the OWL classes). They describe the features of specific objects. For example, the Address class has defined data properties such as address_country_name of type xsd:string, address_post_code of type xsd:string address_city_name address_building_number, address_flat_number, and so on. Parking class has a data property parking_capacity. The other class, voice, has data properties such as filename, filePath, fileURI, and fileType, representing recorded sounds.

In order to represent specific objects in the ontology, individuals have been defined. Simply speaking, individuals can be considered specific objects of the abovementioned classes. For example, the pedestrian crossing across Sienkiewicza Street is a specific individual of the Pedestrian_Crossing class.

Other elements of ontology are object properties. They are used in OWL language to describe binary relations between two things - individuals. The relevant relations have been defined:

- appliesToPedestrian – it has been used to define a restriction that says that only one object (individual) of the Traffic Light class can apply to exactly only one object (individual) of the Pedestrian Crossing class.
- hasDirectNeightbor - allows determining the following elements of the route and says that one element is a neighbour of another object. Using this, we can construct chains of individuals that consist of the route.
- location – each object (individual) can have exactly one Location on the map expressed by address and/or GPS coordinates.
- isLocatedOn – is mainly used to express that something is located in the direction the blind is moving.
- recordedInTheLocation – this property is used to assign a sound to a specific location. For example, the sound can represent cars driving on the street. Considering the direction of the user's movement, this sound can be played on the left or right channel.

The above class hierarchy proposal is not closed. It can be expanded with new classes as needed. However, in the example application described in this paper, the ontology has been simplified to create a game board on which the user moves. The only few following individuals were created in it:

- Building - an object representing a building. There are eight types of buildings available. The building type is randomly selected when the city is generated.
- Car – an object representing a car.
- Player – represents a player
- Point – an object representing a score point. Collecting them is the main goal of the game. Once a point touches a player, that object is removed, and the player's score is increased by one. After collecting all points, the game ends.
- Tile – tiles are the main building block of the world map. Each Tile has an assigned type, e.g., road, intersection, building, or sidewalk. Depending on the type, a different object is generated in place of the Tile.
- TrafficLight – depending on whether the light is on, the signal emits different sounds. The signalling device has a time counter. After a certain period, the lights change. The time after the lights change can be controlled using the "Switch Time" property.

3.1 Binaural Sounds

Due to the lack of visual experience, blind people perceive their surroundings using other senses. The most frequently used senses are, of course, the senses of touch and hearing. Their training and use are referred to as sensory substitution [14] because the sense of sight is, in this case, replaced in functionality by other available senses. By hearing sounds and recognizing their direction, intensity, and type, blind individuals can build an image of the surrounding space in their imagination. Some blind can also echolocation [19] phenomena, i.e., hearing sounds reflected from significant size obstacles such as building walls, bus shelters, or even poles or parked cars. Therefore, the recently emerging possibility of creating the so-called Binaural sounds makes it possible to create technical solutions to support blind people in independent navigation and to train them in related skills. Therefore, the second part of the VSR reality proposed in this article is a set of binaural sounds associated with some objects of the ontology described in the previous section. Binaural sounds are acoustic signals that can be heard from any direction, both horizontally and vertically, using ordinary headphones. However, appropriate methods must be used to create them. One such method is their artificial generation. Given several monophonic sounds, a binaural sound can be generated using a special filter called the HRTF (Head Related Transfer Function) [22]. It is a function that modifies the intensity and frequency of the sound wave, imitating its reflection from the listener's head, chest, and ears in the same way as it happens in reality. Thanks to it, we can simulate not only the direction and distance of the incoming sound but also the effect of its movement relative to the listener. When we record such a modified sound on four channels in a stereo pane (two channels per side), we will receive binaural sound, This sound is heard similarly to the ambient sound in a 360-degree perspective around the listener's head. The only problem with this method is that the sounds produced seem artificial to the listener. The scene surrounding the user must be composed of several separate sounds, such as footsteps, driving cars, passers-by talking, etc.

The second method of obtaining binaural sound is to record it using special directional microphones placed at appropriate angles in four different directions. Using this method, we obtain natural-sounding acoustic scenes. However, the problem here is that to reflect many real situations, we have to record many different fragments of scenes and then dynamically combine them into more extended scenes.

In the implementation of VSR described in this work, the first of the mentioned methods was used. A library included with the Unity environment was used to generate binaural sounds using the HRTF function. Then, scenes consisting of binaural sounds moving about the listener were added to the game.

4 Experimental design of orientation training support

The game proposed in this work was created to facilitate learning spatial orientation skills for blind individuals. It focuses mainly on exploring the area of a randomly generated artificial city and collecting coins located on sidewalks in various places.

The game menu is the first scene that appears after launching the application. Its simple interface makes it easy to navigate through the available options using the keyboard and speech messages emitted by the user. In total, the menu offers four options to choose from.

- ”Start,” - starts the game.
- ”Help” - takes the player to a menu containing a description of the game controls.
- ”Scoreboard,” - where the user can check the top ten scores achieved in the game.
- ”Exit,” - ends the game.

A vital application element is a voice system (speaker) informing the player of the selected option.

After starting the game, a city map is randomly selected from several available maps. The maps were generated with Tiled.1.11.0 tool [25] then converted to a CSV text file and appended to the game's main scene. The maps contain roadways, sidewalks, intersections, built-up areas, and areas free from buildings. Then, the system randomly designates ten places where coins are placed on the map. Coins are only placed on sidewalks for the player to collect. All maps have a structure consistent with urban metrics, i.e., all streets are perpendicular. A sample city map is shown in figure 2.

Car objects are also generated while setting up the game, and the routes they will move are determined. The routes are randomly generated, just like the street section and the direction of the car's movement. If the section ends at an intersection, the further direction of the car's movement is selected: right, left, or straight. Of course, if the street ends with one curve, it is added to the route. Cars move at a constant speed, and they stop when the red lights at the intersection are on. Streetlights' lighting and colour changes are also randomly generated for all intersections, and each light cycle lasts 20 seconds. During the game, the players can hear the cars and the sounds of running engines. These are also binaural sounds, thanks to which the user can recognize whether a car is passing, for example, in front of him, from right to left, or from behind to the road on the right. By listening to these sounds, the player can determine in which direction the nearest road is, which sidewalk he is on, or whether he is approaching an intersection. It is crucial because if the user is on the road and a car is there simultaneously, a collision will occur, automatically ending the game.

During the game, players can move around the map in four directions using the W, A, S, and D keys. The letter keys move the user in the designed direction, and the right and left

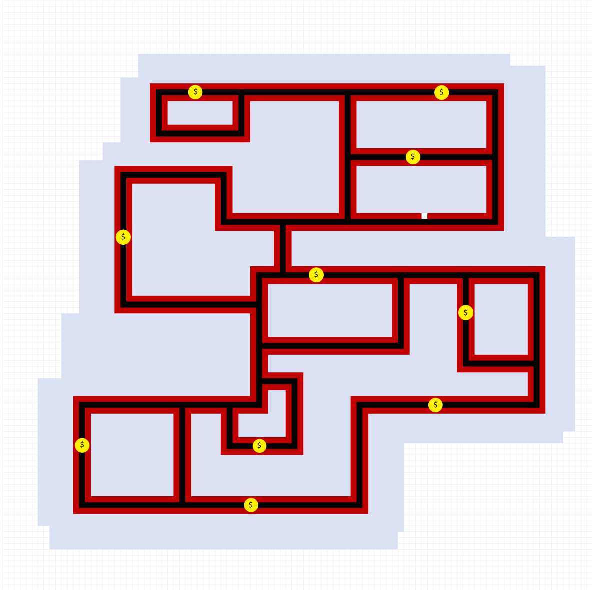

Figure 1. A sample city map

cursor arrow keys rotate the camera. Nothing special will happen if the user goes outside the area defined by the city streets. The only effect is that all sounds become quieter and quieter. To return to the city, the player should follow the direction from which he hears the sounds.

Situations at intersections are regulated by traffic lights that change every 10 seconds. When the user approaches an intersection, cars stop when the light is red and continue when it is green. Another sound signal is generated to inform the user about approaching an intersection. It is similar to the sound we can listen to in natural city traffic lights. It is also a binaural sound that changes direction and volume as the user changes his position. This lets the player know whether he is approaching an intersection with traffic lights. The third type of sound is generated in the places where the system placed the coin. If the player steps into its place and causes the sound to be precisely in the middle between the two stereo channels heard in the headphones, the coin is added to the pool of his score, and the player is informed about this fact via a voice message.

To finish the game successfully, the player must collect all the points on the map, which takes them to the summary screen. The game's leading window example is shown in figure 2.

The leaderboard is the last scene shown to the user after finishing the game. It is a panel that stores information about players' results. The player can access the leaderboard from two places: the main menu during play and after completing the game. However, before the player can access the leaderboard, a summary panel appears with a form in which the player must enter his name. After entering the data, the result is saved to the database, and the results table is displayed. Several players can play the game simultaneously. Therefore, the summary table presents the results of all participants. The summary table contains information about results

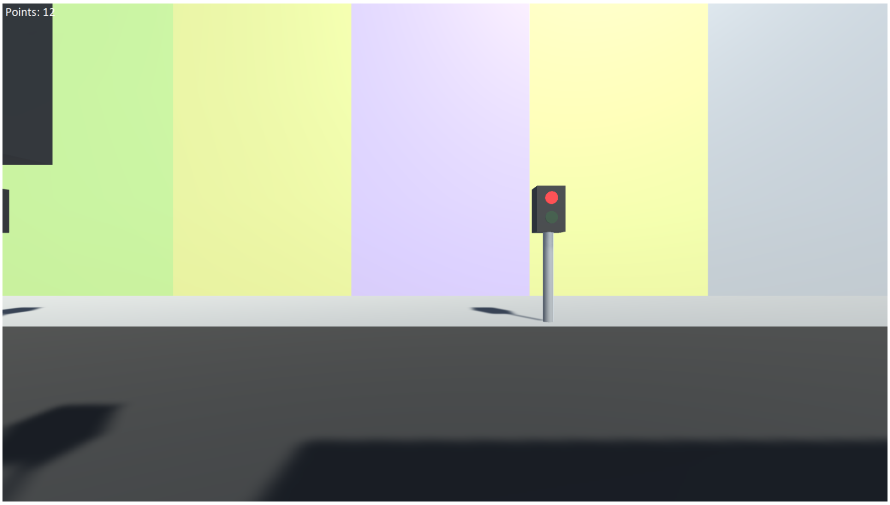

Figure 2. Main window of the game. Source: own study.

and has three columns: player name, obtained amount of coins, and game completion time in seconds. The example of the summary table is presented in figure 3.

5 Conclusions and future works

This paper presents a simple implementation of Virtual Sound Reality, which is intended to help blind people develop spatial orientation skills. Thanks to such implementation, blind users, both beginners and more advanced ones, can improve their spatial orientation skills in low-stress home conditions with a computer and headphones.

The VSR concept consists of an ontology describing the user's space and binaural sounds constituting a representation of this world adapted to its specific needs. This implementation simplified it to a randomly generated city board, moving cars' movement, and using several binaural sounds generated automatically.

The game was tested by Three blind users who generally expressed positive feedback on its concept. However, they give a few comments and suggestions: The first issue is the comfort of use. The ease and intuitiveness of the user interface is significant for blind users. The testers also suggested adding a short manual before playing the game and expanding it with a few features. They had some difficulty in precisely positioning their cursor in the place where the point was so that the system would add it to the pool of points scored. They also emphasized that this feature develops concentration and enhances spatial orientation skills. Users also suggested that additional signals, such as the sound of tapping a white cane on the ground, should inform whether they are moving or standing still, similar to what happens in reality.

The game was implemented at a frame of engineering work [23] using Unity environment with an additional library for generating binaural sounds. So, it still requires some expansion and improvement. Since the problem of using binaural sounds in combination with ontology

Figure 3. Results table for players.

to support blind people in learning navigation is not simple, the game presented in this paper can be seen as the first step in broader research on this topic. Its goal was to confirm the validity of the concept of Virtual Sound Reality in supporting spatial orientation skills.

Although the first fundamental step in this research was taken, the biggest challenge with any simulated training, whether game-based or otherwise, is ensuring that the skills learned in the simulation transfer to the real world. Even with binaural sound, a game environment inherently differs from a complex, dynamic city. It is challenging to replicate the sensory richness, unpredictable events, and emotional factors that influence real-world navigation. Therefore, simulation environments that support learning spatial orientation and mobility should combine more elements of artificial reality. Perhaps future research should develop them as hybrid solutions with physical devices such as a white cane and appropriate substrates or actual objects supported by digital technology.

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