AUDITORY AND HAPTIC SPATIAL COGNITIVE REPRESENTATION IN THE CASE OF THE VISUALLY IMPAIRED PEOPLE

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Navigating in an unknown environment is a difficult task for the visually impaired people, as they are required to rely primarily on the haptic or auditory cues, in compensation for the lack of sight. However, their orientation and mobility skills are well developed, although the process of building a solid spatial cognitive map of the environment can be rather long and sinuous. The main inquiry that emerges from this matter is whether they are able to virtually learn the architecture of an environment by adapting to the specific auditory and haptic cues that define the setting and to transfer their knowledge into real-world, physical contexts. As the spatial audio technology is capable to render individual sounds at desired locations and to design complex auditory scenarios though binaural sound synthesis, the purpose of virtual auditory environments has extended from localization tests to investigating higher-level cognitive abilities. This paper aims to investigate and discuss the most relevant studies and experiments concerning the ability of visually impaired people to adapt to novel environments, to successfully navigate them virtually by using auditory or haptic cues and to construct a mental representation of the surrounding space. The motivation underlying our research is twofold: firstly, it is aimed to contribute to documenting the way in which the visually impaired people spatially perceive the environment and secondly, to provide insights for the development of a virtual reality navigational device based on auditory or haptic (vibrotactile and kinesthetic) events. Taking into account the findings of our research on the ability of blind individuals to carry out effective cognitive tasks and spatial mental representations, we will also discuss future perspectives for the development of an assistive VR system that would facilitate navigation, orientation and overall spatial awareness.

1. Introduction

Building solid mental maps of the surrounding space is an essential prerequisite for the development of effective orientation and mobility skills that are required for navigating unfamiliar settings. Environmental exploration is based on the dynamic combination of locomotor, sensory and cognitive tasks. Spatial orientation allows humans to locate scene elements and facilitates the interaction with the environment by helping them to reach targets, avoid obstacles, improve orientation and determine their own position in respect with the surrounding objects. Sight, hearing and touch are the sensory modalities that play a fundamental role in spatial perception, as they provide the means of identifying the geometrical characteristics of the environment (size, shape, directionality), as well as determining its depth or spatiality. The brain continuously processes and integrates information from these senses and builds a complex image of the surrounding space that is commonly referred to as the spatial cognitive map of the environment. The sense of touch provides information concerning the elements of the near space, while hearing and vision are able to deliver perceptual knowledge about the objects and events located in the far space, with the remark that hearing is an omnidirectional sense, while the visual field is limited to the frontal plane of the observer [1]. For navigating in an unknown environment, the sighted people use primarily the visual information that is acquired continuously and spontaneously. Thus, as most of the spatial information is acquired through the visual sense, the blind people are seriously deprived of a means of actively interacting with the environment the way that the sighted people do. As a result, they face considerable difficulties in generating a detailed and accurate spatial representation for navigating in their extrapersonal space. However, the visually impaired individuals have developed their ability to navigate unfamiliar settings by relying on the auditory and haptic cues as the main exploration modalities [2]. We therefore support the idea that providing the adequate spatial information through an alternate sensory channel can contribute to the development of a solid spatial cognitive map of the environment and consequently improve the blind individuals' navigational performance. Moreover, as the construction of a spatial mental representation is a long and time-consuming process, we consider that the visually impaired people can successfully benefit from navigating virtual environments prior to the real ones. Thus, they can learn the spatial configuration of an environment by listening to auditory events or by perceiving the haptic (tactile and kinaesthetic) sensations that build up the virtual reality experience [3]. In the last years, the virtual reality techniques have significantly advanced, providing a natural interaction modality between the end-users and the virtual environment. The computer-generated environments offer a wide range of sensorial virtual experiences, most of them visual, but also auditory and haptic. The main advantage of virtual reality technology is that it provides the means for studying and investigating the human cognitive behaviour, without having to consider the cost and setup of physical environments [4].

This paper aims to investigate the way in which the blind people are able to learn the configuration of a new space by using auditory and haptic cues as the basic means of interaction in either real-world or virtual environments. The motivation of this study is twofold: first of all, it focuses on investigating the modality in which the blind people are building a mental model of the surrounding space and secondly, it is aimed to provide insights concerning the development of assistive systems for the visually impaired based on alternate sensory channels, such as hearing and touch [5].

2. The formation of cognitive maps

The formation of cognitive maps is influenced by the image scanning process (the constant shift of attention from one object to another in the visual field, aimed to discriminate the components of the visual scene or to focus on a specific details of one target). The purpose of our review is to determine the extent to which the acquisition of spatial information by other means than the visual sense (for instance, by using the auditory and haptic alternative sensory channels) can result in internal cognitive representations that have the same particularities for the blind or visually impaired people as the vision mediated image scanning has for the sighted individuals [6]. Cognitive mapping refers to the ability to synthesize the spatial information and to transform the perceptual stimuli into consistent spatial knowledge and understanding of the environment. Additionally, cognitive mapping is related to the process of storage, recall and decoding of the information concerning the characteristics and general attributes of the spatial environmental phenomena [7]. The cognitive mapping, as the internal representation of the world, plays a fundamental role for providing a sense of spatial awareness, improving the wayfinding and navigational abilities and refining the orientation and mobility skills. According to Jacobson [7], investigating the cognitive map formation of the blind and visually impaired people is a subject of considerable significance, both theoretically and practically. Thus, he identified four motivations for studying the spatial cognitive representation of the vision-deprived individuals. Firstly, cognitive mapping research is able to improve the mobility and independence of the visually impaired people, to enhance the wayfinding and navigational decision-making abilities and to ameliorate their quality of life. Secondly, the cognitive mapping research is able to provide a rich theoretical and practical documentation for the development of assistive devices for the blind and visually impaired users, concerning the information that needs to be encoded and the modality in which it needs to be presented to the traveller. Moreover, cognitive mapping research can investigate the utility and proficiency of the assistive devices in order to assess their degree of efficiency in providing a rich spatial representation of the environment. Third, the results obtained from the study can be integrated in the development of environmental planning schemes to facilitate blind people interaction. Finally, the insights and understanding provided by the cognitive mapping research conducts to a better theoretical documentation concerning the role of sensory experience (either visual, acoustic or tactile) in the formation of spatial images in general.

The mental model of the space incorporates information about spatial relations between the objects, metric distances and other object-related characteristics of the environment. It has been argued that the early blind individuals are able to process the spatial information statically, but they have difficulties in integrating it in a single, unitary perceptual image, due to the lack of mental abstraction required for this type of task. The opinions concerning the spatial abilities of the visually impaired individuals are contradictory in the scientific community. Some studies demonstrated that vision is an essential prerequisite for the development of solid spatial representations, while other researchers demonstrated that the visual stimuli are irrelevant to the formation of effective cognitive maps [8]. For instance, Klatzky [9] showed that the differences between the spatial performance level of sighted, early-blind and late-blind subjects are slight, suggesting that the mental model construction of the environment is not dependent on any prior visual experience.

3. Assistive devices for the visually impaired people

The orientation and mobility information that is necessary for navigating in unfamiliar environments should be provided at both perceptual and conceptual levels [2]. In what concerns the perceptual level, the lack of visual information should be compensated by the use of alternative sensorial stimuli, such as auditory or haptic cues. Regarding the conceptual level, the interest is focused towards the development of the adequate procedures for effectively mapping the space so that it would sustain a comprehensible and practical navigation for the visually impaired users. The humans use 2 main strategies for scanning the extra-personal space: route strategies, which refer to the sequential identification of spatial characteristics and map strategies that are based on acquiring the spatial features and components of the environment from a larger, multi-layered perspective. The blind people use primarily the route strategy for navigation, as they identify and recognize the objects and events linearly and consequently bring together all the information to construct a single, unitary image of the space [2].

The Electronic Travel Aids, the assistive devices that offer mobility to the visually impaired people, can be divided into 2 categories: obstacle detectors (based on laser beams and ultrasound), that offer information about the objects located in the close proximity of the user and environmental imagers, which deliver an acoustic (or auditory-haptic) image of the 3D space. The obstacle detectors present the disadvantage that they are not able to provide a full perception of the environment while, on the other hand, the environmental imagers require a long training procedure and a high degree of distributive attention for analysing and responding to all the acoustic or haptic stimuli that are delivered to the user in compensation for the lack of sight [1].

4. Sensory substitution

Sensory substitution is an alternative method that helps the blind people to acquire information about the surrounding space by encoding the visual information into tactile or auditory stimuli. It has been demonstrated in various experiments and studies that the visually impaired individuals are able to effectively process these stimuli in order to develop a solid spatial cognitive map of the environment as sighted people do, in the area of the brain that is responsible for the synthesis of visual cues, i.e. the primary visual cortex. Sensory substitution cannot be considered as a pure sense, as it is neither pure vision nor pure hearing, but a subjective perception known as “qualia”. This is due to the fact that sensory substitution is processed in the cortical areas of the brain, but it receives acoustic and tactile sensations from the basic receptive levels (the auditory or the tactile-kinaesthetic systems). It has been suggested that the brain areas are “metamodal”, so that the cortices are assigned different functionalities for processing various types of information and not for responding to different sensory modalities. For example, the primary visual area can be elected for processing spatial information, even if it comes in the form of auditory or tactile stimuli and not compulsory as visual stimuli. A certain level of crossmodal plasticity has been recorded as a result of training and long-term development, by establishing strong connections between senses during echolocation, sound localization and Braille reading that resulted in an increased visual activation in the case of early and late blind individuals. Apart from activating the visual cortex, sensory substitution also provides a vision-like perceptual experience, such as the perception of colours or associations with the visual images acquired before the onset of blindness [10].

For instance, the study of Ortiz et al. [11] demonstrated that almost half of the blind subjects who participated in an experiment that involved the use of tactile sensory substitution device recorded phospenes (a phenomenon of seeing light). In most of the cases, the phosphenes corresponded to the direction and shape of the tactile stimulus presented. The results are reinforced by EEG measurements that showed a certain degree of activation in the occipital lobe (the visual cortex) in the case of the blind individuals that claimed to have vision-like perceptual experiences. A special issue that occurs in vision-like perception is the occurrence of visualization, especially in the case of late-blind subjects who have experienced vision in their lives and could be able to activate the visual cortex via visualization or to imagine that they see and object or a scene. The most relevant evidence against visualization in the case or the blind subjects from Ortiz’s experiment is that the light perception appeared automatically and that the tactile sensations diminished as the visual experiences became more dominant [10].

The vision-like processing is further supported by neural imaging and stimulation studies. For example, PET studies [12] showed activation in the visual occipital cortex of the blind participants, but not for the sighted subjects. Another fMRI research [13] demonstrated that the lateral occipital tactile-visual area can be stimulated by using a sensory substitution method for performing object detection and shape recognition tasks.

4.1 Auditory cues

The hearing sense offers directional and depth perceptual information regarding the targets located both in the near and in the far space. By performing head movements, the ears gather essential information (direction, duration and intensity of the stimuli, distance and range) that converge to the formation of the auditory array that is further processed at a higher level to build up the so called cognitive spatial map [14]. The audio information is essential for the development of spatial and navigational skills. The auditory sense does not require direct contact with the world, as it can be successfully employed in both indoors and outdoors conditions, in both active exploration (where the position of the listener changes in respect with the location of the acoustic targets dynamically) and for passive observation (when the listener is simply an observer who acquires information statically, without interfering with the environment in any way) [7].

The complex sound environments are known as soundscapes [15]. The soundscapes can be described as a subjective listening experience that is different for each person [16]. The multiple sounds that are present in the environment simultaneously can draw the listener's attention in different ways, concerning both their physical properties (intensity or pitch) and their significance and relevance to the listener. Soundscapes are considered to be the acoustic correspondent of landscapes, as they can be segregated into background and foreground sections that are perceived and analysed perceptually and cognitively both consciously and subliminally [14].

3D acoustic spatialized systems give the listener the impression that the sound he hears comes from a particular direction in space and that he is surrounded by sound sources all around in the three-dimensional environment in which he is immersed [17]. The use of binaural 3D sounds in virtual reality applications can prove to be beneficial for investigating the spatial perception, sound localization accuracy, orientation and mobility skills and navigational proficiency of both sighted and blind people, without the need of building any physical environments. The applications that build acoustic 3D spaces based on spatialized sounds are commonly referred to as auditory display systems. Recently, they have also been integrated in electronic travel aid devices aimed to deliver an accurate representation of the space through binaural auditory cues [1].

4.2 Haptic cues

Tactile maps are used to convey information about the spatial components of the environment and also as an important aid for wayfinding, navigation and mobility learning, with the purpose of extending the knowledge about the environment beyond the practical and physical experiences acquired from direct exploration. The audio-tactile multimedia approach is the result of the combination of tactile and auditory cues in hybrid applications that enhance the spatial perception by applying sound labels to the graphical elements of the maps. The sound stimuli can be synthesized speech or auditory icons (nonverbal audio messages, like the sound of a door opening or the noise of a crowded street). They improve the navigation of the map, provide a rich representation of the environment and replicate the real-world settings at a smaller scale level [7].

5. Auditory and haptic cues in spatial localization experiments

The study presented in [6] investigated the spatial cognitive map formation of three categories of subjects (sighted, early and late blind) in two different experiments. In the first experiment, the participants learned the spatial configuration from verbal description and from active haptic exploration. In the verbal condition, the subjects were required to listen to a spoken text describing a circular island on which six geographical landmarks were positioned. In the haptic condition, a metal map of the island (containing six tags corresponding to the six landmarks) was presented to the participants. During the learning phase, the subjects were required to learn the position each of the landmarks and to repeat their description aloud (the name of the landmark and its position). For the haptic condition, the experimenter positioned the dominant hand of each participant along the edge of the map and indicated for each tag which landmark is referred to. After the haptic exploration, the magnets were removed and the participants were asked to position them again and to recall their correct location. During the test phase, the subjects were required to reconstruct mentally the map of the island and to position each landmark at its correct location on the map. The results showed that the blindfolded sighted and the late blind participants were able to build an effective representation of the spatial configuration that preserved the topological organization and distance relationship between the constitutive items of the map under both conditions. On the other hand, the congenitally blind encountered troubles with the metrical representation of the space and showed a much longer scanning time than their late blind or sighted counterparts. In the second experiment, the subjects were immersed in a real environment and were provided a virtual acoustic scene in which six virtual sounds were located by actively exploring the environment. After learning the sound stimuli, the subjects were asked to discriminate from a set of cues which of them are part of the learned environment and which are not. In this experiment, the blind participants obtained better results than the other two groups when using locomotor and auditory cues, demonstrating that the ability to elaborate a metrical spatial cognitive map is facilitated by locomotion and sensorimotor experience in conjunction with listening to 3D audio cues [6].

In the experiment displayed in [5], two virtual acoustic environments have been developed by using real-world sound stimuli (3D spatialized sound) and other graphical architectural elements. The subjects used a joystick as the main navigational device, stereophonic headphones and a head-tracking device. There have been two experimental conditions: a real-world and a virtual navigation condition. The participants (congenitally and late-blind individuals) were required to navigate two different corridors along which various sound sources were positioned. The evaluation of the spatial knowledge acquired was performed through a Lego blocks reconstruction session and a test concerning the metric characteristics of the settings. The results for the real and virtual navigation are comparable, showing a high level of improvement in the quality of the mental mapping. Moreover, the authors identified a significant occurrence of the symbolic distance effect, situation in which the respondents misjudge the distance between two locations in the case of small differences. For both navigational conditions, the estimation of medium and large distances is very precise, demonstrating that the blind people are able to create a mental metrical and topological spatial representation of an acoustic environment [5].

The approach proposed in [18] describes a virtual sound maze through which the player navigates via a game controller. The virtual auditory environment uses 3D sounds that are delivered through headphones and a head tracking device mounted on the head of the user. The spatial acoustic perception is enhanced by adding sound reflections from the walls, echoes, reverberation and other auditory effects. The experiment assessed the subjects’ (four congenitally blind and four sighted persons) ability of building tactile maps after navigating the virtual acoustic maze. Also, they were required to navigate through a real-world setting that had the same physical characteristics as the virtual acoustic environment that was explored previously. The results revealed that the subjects were able to build solid cognitive maps and to complete the task of accurately navigating the physical environment based on 3D sound cues.

In [4], a large immersive auditory environment was designed in order to study the effect of vision on the construction of mental representations of the space. The experiment took place in a room (both physical and virtual) that contains six familiar virtual sound targets. The architecture of the environment consists of walls and floors, collision detection warnings and sound objects. The experiment involved the participation of 45 subjects (blindfolded sighted, early blind and late blind individuals). For half of the subjects, the learning phase consisted of a verbal description of the position of the sound sources (using the conventional clock positions). For the other half of participants, the learning phase was a physical, active navigation to each sound source. During the experimental phase, the subjects were presented a sound and they were required to identify its position. The results demonstrated that the active exploration of a virtual acoustic environment improved the sound localization abilities and the spatial map formation of all the researched subject categories to a larger extent than verbal descriptions [4].

The study described in [2] presents a multimodal-virtual-learning-environment (MVLE) based on haptic and auditory cues. The experiments involved the participation of two groups of early and late blind subjects. The experimental group navigated the virtual environment and their results were compared with the control group of subjects who explored a real-world setting directly. Following the navigational task, the subjects were required to describe the environment, to build a scale model of it and to perform some orientation and mobility tasks, such as finding an object in space or remapping the settings by accessing a different entrance. The results showed that the subjects from both groups were able to build an accurate model of the spatial configuration, although the cognitive map constructed by the subjects from the experimental group was more detailed and precise, as indicated in their verbal and physical descriptions. Moreover, the subjects from the experimental group performed with better accuracy than the control group in the target-object search task (by choosing shorter and more direct paths), demonstrating enhanced orientation and mobility abilities. In conclusion, the use of a virtual environment (constructed upon a wide range of haptic and auditory feedback cues) provided the blind subjects the efficient means for building a comprehensive and thorough spatial representation of the spatial configuration and significantly enhanced their navigational skills [2].

6. Conclusions

Even if vision is considered the most reliable sense that connects us with the exterior world, it has been demonstrated that the blind people are capable to use other senses – touch, hearing or even smell, to gain awareness of the environment and to effectively acquire spatial information. The study of the formation of cognitive maps in the case of the visually impaired individuals is a subject of considerable worth, both theoretically and practically. Thus, it provides a thorough understanding on how to design training methods for improving orientation and mobility, offers information about the navigational strategies employed by the visually impaired people to the designers of travel aid systems and gives valuable insights concerning the role of sensorial experience in the development of spatial cognitive maps. The study presented in this paper is a starting point for a more rigorous, in-depth research, aimed to provide clear evidence about the modality in which the blind people perceive the extra-personal space. The theoretical information acquired from this and from other studies needs to be integrated in feasible projects that would have a practical goal, such as the development of assistive devices, blind-accessible software or audio games for the visually impaired users.

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