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Exploration of architectural spaces by blind people using auditory virtual reality for the construction of spatial knowledge ☆

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ABSTRACT

Navigation within a closed environment requires analysis of a variety of acoustic cues, a task that is well developed in many visually impaired individuals, and for which sighted individuals rely almost entirely on visual information. For blind people, the act of creating cognitive maps for spaces, such as home or office buildings, can be a long process, for which the individual may repeat various paths numerous times. While this action is typically performed by the individual on-site, it is of some interest to investigate at which point this task can be performed off-site, at the individual's discretion. In short, is it possible for an individual to learn an architectural environment without being physically present? If so, such a system could prove beneficial for navigation preparation in new and unknown environments. The main goal of the present research can therefore be summarized as investigating the possibilities of assisting blind individuals in learning a spatial environment configuration through the listening of audio events and their interactions with these events within a virtual reality experience. A comparison of two types of learning through auditory exploration has been performed: *in situ* real displacement and active navigation in a virtual architecture. The virtual navigation rendered only acoustic information. Results for two groups of five participants showed that interactive exploration of virtual acoustic room simulations can provide sufficient information for the construction of coherent spatial mental maps, although some variations were found between the two environments tested in the experiments. Furthermore, the mental representation of the virtually navigated environments preserved topological and metric properties, as was found through actual navigation.

1. Introduction

Spatial audio technology has long been used within virtual reality (VR) applications both for recreational purposes (e.g. video games) and for studies relating to human perception, primarily in the area of auditory source localization. The ability to render individual sounds at desired positions or to create complex spatial audio scenes, without the need to manipulate any physical equipment, has offered researchers many advantages. Recently, the use of spatial audio has expanded beyond the study of low level processes such as localization, and is being used as a tool to investigate higher-level cognitive functions. The research presented in this paper results from collaboration between researchers in psychology and acoustics on the issue of spatial cognition in interior spaces.

Navigation within a closed environment requires analysis of a variety of acoustic cues, a task that is well developed in many visually impaired individuals, and for which sighted individuals rely almost entirely on visual information. For blind people, the creation of cognitive maps for spaces, such as home or office buildings, can be a long process. The individual may repeat various paths numerous times, without anybody present in the environment, in order to be able to hear all the relevant acoustic information. With this acoustic input, the individual is capable of constructing an accurate and useful mental representation of the space. While this action is typically performed by the individual on-site, it is of some interest to investigate to what degree this task can be performed off-site, at the discretion of the individual, using a virtual simulator.

As an example case, consider the situation of a blind person beginning a job in a new environment. It is common for him/her to begin by visiting the building late in the evening (when few people are present), and actively exploring the spaces in order to acquire some knowledge of the spatial configuration and of the basic features of the architectural layout and acoustic landscape (e.g. reverberation changes, background noises, sounds of footsteps on different floor finishes). The goal of this research is to

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carry out a feasibility study for investigating whether a visually impaired person would be able to collect this acoustic information – which is vital to their understanding of an environment and thus to their quality of life – by means of an interactive audio VR system which has been designed to deliver a realistic 3-D soundscape of the environment.

In short, is it possible for an individual to learn an architectural environment without being physically present? If so, such a system could prove beneficial for navigation preparation in new and unknown environments.

The motivation of the present research is therefore twofold. First, its aim is to contribute to documenting the processes by which blind people construct mental representations of their surrounding space. Secondly, it is intended to provide grounds for the design of systems delivering audio information to assist blind people in their spatial orientation and navigation of interior spaces. This is to be achieved through a feasibility study whose results will be employed for further future development and evaluations.

A comparison of two types of learning has been performed: *in situ* real displacement and active navigation in a virtual architecture. For both conditions, only acoustic information was available (participants were not allowed to use a white cane or be accompanied by a guide dog).

2. Background

This study does not present the first use of spatial audio technology and VR applications for investigating auditory performances of blind individuals. Nevertheless, the use of these technologies for exploring and evaluating spatial hearing processes and high level cognitive mechanisms can be considered as being particularly novel. This section presents previous relevant studies concerning blind people's spatial auditory perception and use of interactive VR environments in cognitive studies.

A detailed literature review, as well as background studies related to the current work, can also be found in Katz and Picinali (2011a).

2.1. Spatial auditory perception of visually impaired people

It is a common belief that blind individuals have a heightened auditory sense when compared to the general sighted population. Numerous studies have been carried out in an attempt to examine this claim, focusing on different aspects such as spatial precision, response time, brain activity, and neural plasticity. Previous studies have used either real sound sources (speakers) or virtual auditory displays (VAD) with binaural renderings.

As a baseline reference, Starlinger and Niemeyer (1981) conducted a series of audiological threshold tests for 18 blind and 18 sighted individuals. Comparisons for intensity, inter-aural time difference, and auditory reflex thresholds found no significant differences. Frequency discrimination thresholds were significantly, though only slightly, improved in blind individuals.

A collection of studies focusing on spatial audition has shown a clear tendency of improved capacities in blind individuals. Focusing on central auditory system tasks, Muchnik et al. (1991) compared localization, temporal resolution, and speech extraction in noise. In comparing groups of congenital or early blind, late blind, and sighted controls (each group comprising about 10 individuals), blind participants outperformed the sighted control group. In contrast, Zwiers et al. (2001) found that elevation localization, tested in the frontal square area, deteriorated more for blind participants in low signal-to-noise conditions as compared to sighted controls, although this was tested for only a small participant population. Doucet et al. (2005) found that blind individuals had better azimuthal localization performance in the presence of spectral degradations, implying that blind individuals are better at processing spectral cues. While not specifically studying spatial audition, Röder and Rösler (2003) found that blind participants exhibited better memory for sounds, also indicating improved processing of spectral information.

Ashmead et al. (1998), in addition to providing a thorough bibliographic review on spatial audition studies, presented a study comparing minimum audible angle (MAA) for azimuthal changes, showing that blind children outperformed or performed comparable to sighted adults, both being better than sighted children. Considering frontal horizontal sources, Dufour and Gérard (2000) showed that improved auditory localization performance extends to near-sighted individuals as well.

A number of studies, such as Weeks et al. (2000), have focused on evaluating neural plasticity, or changes in brain functioning, for auditory tasks executed by blind and sighted participants. Results by both Elbert et al. (2002) and Poirier et al. (2006) have shown that blind participants exhibit increased activity in areas of the brain which are typically considered visually oriented.

2.2. Human–computer interfaces for blind people

Various human–computer interfaces particularly relying on auditory and haptic stimulation have been developed and/or specifically customized for use by blind and visually impaired individuals.

In Evett et al. (2009) an interface was created to allow exploration of virtual environments via only auditory and haptic feedback using a readily available inexpensive system such as the Nintendo WII remote. Systems like this are meant to facilitate the development of accessible games, and thus enable universal design and accessible technologies to become more accepted.

Gomez et al. (2012) created an interface for enhancing spatial awareness and intelligibility for blind users through audio and touch. The core of this interface was the codification of color and depth information into musical instrument sounds, which provided spatial awareness and information about boundaries and obstacles. This allowed blind individuals to selectively explore environments, discover points of interest, and develop personalized navigation strategies.

Furthermore, Loomis et al. (2001) compiled a complete review of GPS-based navigation systems for visually impaired people, stressing the value of such systems for their navigation in outdoor environments. As regards indoor spaces, Loomis et al. (2005) pointed to the fact that GPS does not work fully in such contexts and that other methods are to be considered (see also Sánchez, 2009). For instance, Gill (1996) developed a solution based on infrared technology standards working as sensors to determine a traveler's indoor location. In a similar perspective, the Drishti system (Ran et al., 2004) was designed by combining GPS for outdoor navigation and ultrasonic sensors for indoor navigation.

While outdoor navigation systems for blind people have received extensive attention in the past years (cf. Gallay et al., 2013), indoor navigation aides are less developed, requiring further study. This is accomplished in particular through the identification of indoor wayfinding principles for blind people and the development of specific indoor routing algorithms (see Swobodzinski and Raubal, 2009). Two recent examples can be mentioned. Serrão et al. (2012) have designed a system which integrates a Geographic Information System (GIS) of a building with visual landmarks for localizing the navigating person and for tracing and validating a route for the user's navigation. Riehle et al. (2012) have reported the construction and evaluation of an indoor navigation technology intended to support seamless mobility for visually impaired people. The system infers the user's current