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Evaluation of a Motion Platform Combined with an Acoustic Virtual Reality Tool: a Spatial Orientation Test in Sighted and Visually Impaired People

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Abstract— **To orient and move efficiently in the environment, we need to rely on multiple external and internal cues. Previous studies reported the combined use of spatialized auditory cues and self-motion information in spatial navigation and orientation. In this study, we investigated the feasibility of a setup composed of a motion platform and an acoustic virtual reality tool with sighted and visually impaired participants. We compared the performance in a self-motion discrimination task with and without auditory cues. The results revealed good usability of the setup and increased precision with auditory cues for visually impaired people.**

Clinical relevance— **This preliminary research presents a novel combination of a motion simulator and a simple acoustic virtual reality tool to investigate multisensory perception during passive self-motion stimulation in healthy and clinical populations.**

I. INTRODUCTION

Spatial orientation and navigation are crucial functions in daily life because they allow us to reach a target location when moving through space, relying both on internal and external points of reference. Our brain processes self-motion information perceived by the peripheral vestibular system, encoding linear and angular acceleration of our head to perform these tasks efficiently. Previous studies on patients with vestibular sensory loss have confirmed its essential role for efficient spatial orientation [1]. However, the vestibular system alone does not provide information about the relationship between movement and external references such as environmental landmarks. Landmarks are external objects or locations, which help orient and recognize places as familiar. Therefore, our brain requires to combine information that comes from different sensory modalities to ensure accuracy and precision in self-motion perception. Vestibular stimulation is extensively combined with other sensory modalities and motor signals [2]. Previous literature has shown that vestibular and visual information are efficiently integrated, leading to enhanced precision, e.g., for heading perception [3]. Vision is the most accurate sense to detect spatial cues in the environment [4]: because of its high spatial acuity, the visual system allows the brain to process detailed spatial information. However, there are situations in which vision is not reliable or not available, such as visual impairments. Visually impaired people are clearly at a disadvantage relative to the sighted population during navigation, because not only the visual information generated by self-motion is missing, but also visual representation of the environment in which they are travelling is not available [5]. Visual landmarks in the environment are often associated with auditory information (e.g., a river with the sound of water flowing) and also auditory cues are used to add external reference to the information provided by the vestibular system. In addition, sound is particularly important for far obstacles, and contrary to visual cues, auditory cues remain available even when the head is not directly oriented to the sound source [6]. Moreover, there is a growing body of evidence showing that auditory cues localized in space can improve ambulation [7], self-motion perception [8], and navigation [9]. In this pilot study, a novel experimental procedure is presented, based on the joint use of two newly developed simulation devices. The first is a 2-Degrees-Of-Freedom motion platform, the Rotational-Translational Chair [10]; the second is an acoustic virtual reality tool, the 3D Tune-In Toolkit [11]. The combination of these tools allowed us to test how vestibular self-motion cues and auditory landmarks are combined. Moreover, since visually impaired people need to rely on auditory information to orient themselves, we compared the use of virtual acoustic landmarks between sighted and visually impaired participants in a spatial orientation task. In the present study, we focused on one particular aspect of auditory–vestibular interaction, i.e., the precision in a self-motion discrimination task, with and without virtual auditory landmarks, expecting good usability of the two combined tools.

II. METHOD AND MATERIALS

A. Participants

Five visually impaired (4F; mean age=48±7 y.o.) and nine sighted participants (6F; mean age=28±6.2 y.o.) took part in this study after giving written consent. The clinical details of visually impaired participants are displayed in Table I. The study was approved by the ethics committee of the local health service (Ethical Committee, ASL 3, Genova, Italy) and was conducted in accordance with the Declaration of Helsinki (1964). Ad hoc procedures were applied to sanitize the environment and set-up at the beginning of each session

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TABLE I: Clinical details of visually impaired participants.

Participants	Age (y.o.)	Gender	Pathology	Impairment onset (y.o.)	Residual vision
B01	55	F	Nystagmus and Retinis pigmentosa	30-40	Lights and shadows
B02	44	F	Loss of retina	18	Lights and shadows
B03	44	F	Congenital cone dystrophy	Birth	1/50 both eyes
B04	42	M	Retinis pigmentosa	22	Right eye: 3-5° visual field Left eye: lights and shadows
B05	57	F	Retinis pigmentosa	7	Lights and shadows

and the experimenter and subjects wore devices for personal protection against COVID-19.

B. Experimental setup and stimuli

The experimental setup included the Rotational-Translational Chair (RT-Chair; [10]) and the 3D Tune-In Toolkit tool (3DTI Toolkit; [11]).

- The RT-Chair (see Fig. 1, left panel) is a 2-Degrees-Of-Freedom motion platform, which provides smooth and vibration-free movements and elicits responses from the vestibular organs. In the present study, we selected only rotational movements, which trigger semicircular canals responses. In particular, the motion stimuli consisted of 3-seconds yaw rotations along the earth-vertical axis (0.33 Hz), which followed a minimum jerk motion profile. The rotation angles ranged from 10° to 80° clockwise and -80° to -10° counterclockwise. Peak velocities ranged from 6.25°/s to 50°/s; peak accelerations ranged from 6.41°/s^2 to 51.32°/s^2. The control of the motion platform was established thanks to the implemented Matlab (Matlab2017, The Mathworks) interface.
- We used the 3DTI Toolkit to build an acoustic virtual environment. The simulation of an acoustic virtual reality is accomplished by using binaural spatialization, based on convolving a monaural signal with head-related transfer functions (HRTFs) [see 11]. To associate the 3DTI Toolkit with Matlab, we used a communication protocol previously implemented by our lab [12], which works as explained below. The 3DTI Toolkit's test application receives instructions through Open Sound Control [13], based on wireless (WLAN) communication, a protocol for data exchange among devices. It is based on User Datagram Protocol (UDP), which uses the IP addresses and the port of the communication units. The UDP communication was established in Matlab by creating an UDP object (*udp()* function), while the *oscsend()* Matlab function allowed positioning the sounds where needed with instructions compatible with the toolkit. The right panel of Fig. 1 shows the user's interface of the application. The used auditory landmarks consisted of semantic sounds (duration: 1 second), which resemble an office environment: a working copy machine and water being poured. We downloaded the sounds from a royalty-free website (https://freesound.org/). Relative to the starting position at azimuth 0°, in line with the participant's nose, the copy machine sound was virtually spatialized at azimuth -45° and the water sound at azimuth 45° (see Fig. 2), both at a distance of 1.1 meters. The sounds were delivered over binaural headphones (Sennheiser HD-650), which were used by the toolkit as a playback device.

C. Design and Procedure

Participants sat on the padded racing seat of the RT-Chair. The experimenter explained the task, giving participants the headphones and a wireless numeric keypad. The head of participants was aligned with RT-Chair's rotation axis and leaned against a vacuum pillow, shaped according to the head, with their forehead held with a padded strap to the chair to reduce the potential use of neck proprioceptive cues as sources of information for orientation. During the experiment, the room was darkened; besides, sighted participants had their eyes closed and covered by an eye mask to prevent any use of the room's visual information. Participants performed a two-alternative forced-choice (2AFC) self-motion discrimination task. For clockwise rotations, they reported verbally after each rotation whether they felt to be closer to the point of reference at azimuth 0° (the starting point) or to the point of reference at azimuth 90°. For counterclockwise rotations, they reported whether they felt to be closer to azimuth 0° or azimuth -90° (see Fig. 2). To let participants have a clear reference of the ±90° points of reference, before the experimental session, they experienced four rotations with amplitude 90°, one for each level of the experimental design explained below. We tested two conditions (Vestibular-only vs Multisensory) and two movement directions (counterclockwise vs clockwise rotations). In Vestibular-only condition, participants needed to estimate their movement's amplitude by using only the vestibular cue from clockwise or counterclockwise rotations. In Multisensory condition,

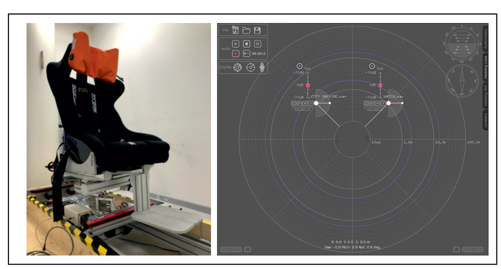

Fig. 1: On the left panel, the RT-Chair; on the right panel, the 3DTI Toolkit user's interface.

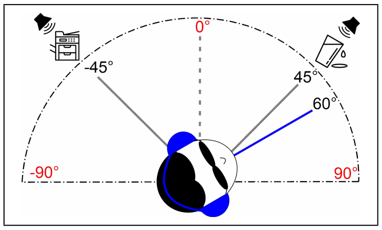

Fig. 2: Experimental setup. At azimuth -45°, it is represented the sound of the copy machine landmark; at azimuth 45°, the sound of the water landmark. The considered points of reference at azimuth -90°, 0° and 90° are highlighted in red. In the example, the participant is rotated 60° clockwise, being closer to azimuth 90°.

participants could rely on both vestibular and auditory cues to estimate the rotations' amplitude. When rotating clockwise, the auditory cue consisted in the "water" sound, placed at azimuth 45°; when rotating counterclockwise, the cue was the "copy machine" sound, placed at azimuth -45° (Fig. 2). Thus, the sounds worked as auditory landmarks that helped recognize the middle amplitude between the reference points at 0° and ±90°. Before each trial, as "GO" signal, a voice through headphones suggested the type of condition: the word "Rotazione" (Italian for rotation) indicated a vestibular-only trial; the word "Audio" (Italian for audio) indicated a multisensory trial. To start each trial, participants pressed one keypad button. Thus, in Vestibular-only condition, right after the pressure of the keypad button, participants experienced the rotation. In Multisensory condition, after the pressure of the keypad button, the auditory landmark was played; right after listening to the sound, the rotation began. When it stopped, the auditory landmark was presented again. To keep the auditory landmark spatialized in the same locations at ±45° after the rotation, the sound was virtually rotated with an amplitude equal to the presented rotational movement but in the opposite direction to simulate a sound fixed in the environment. During all RT-Chair rotations, a white noise sound was played through headphones to mask the sounds elicited by the device. For each trial, the experimenter collected the verbal response and the participant was brought back to the starting point with a movement with reduced frequency (0.25 Hz). To prevent any potential aftereffects between two consecutive movements [14], 3-seconds time window was guaranteed between experimental motion stimuli. The order of conditions was randomized across trials for all participants. In each condition, we tested 54 trials, of which the first four were training trials with fixed movement magnitude. For the remaining trials, rotation amplitude was determined by the Psi adaptive procedure [15] implemented using the PAL_AMPM routine from the Palamedes toolbox [16] in Matlab (total n trials = 216). To prevent drowsiness and fatigue, participants took two breaks at one-third and two-thirds of the experiment. None of them reported motion-sickness sensations.

D. Data analysis

One sighted participant was excluded from the analysis due to a technical issue. For clockwise rotations, we plotted the percentage of responses "I felt closer to azimuth 90°" as a function of the delivered stimulus displacement. Similarly, for counterclockwise rotations, we plotted the percentage of responses "I felt closer to azimuth 0°". For each participant and condition, we fitted a cumulative Gaussian to the data using the PAL_PFML Fit routine from the Palamedes toolbox [16], which finds the best fit in a maximum likelihood sense (Fig. 3). We took the standard deviation of the distribution (the just noticeable difference, JND) as a measure of precision. The estimates' error was calculated by performing a non-parametric bootstrap analysis, running the function PAL_PFML BootstrapNonParametric from the Palamedes toolbox, generating 400 simulated data sets [17]. For each subject, we obtained a JND value for each condition and direction of rotation. Considering that JNDs had not normal distributions, we conducted a non-parametric permutation ANOVA (using the function *ezPerm* from the *ez* package in RStudio 3.6.2, 2019) with Condition as a within factor and Group as a between factor. Since we did not expect any difference in the direction of rotations, we pooled the results of both clockwise and counterclockwise movements.

III. Results and Discussion

To test the combination of a virtual acoustic environment and a motion platform, we compared both sighted and visually impaired people's performance in a self-motion discrimination task. In this preliminary study, statistical analysis on JND showed neither a main effect of the Condition (Perms = 5000; $p = 0.306$) nor the Group ($p = 0.395$) nor interaction ($p = 0.411$). The absence of a statistically significant effect of Condition indicates that the level of precision in estimating the rotations' amplitude relative to external points of reference is comparable between the condition in which only vestibular cues are available and the condition in which the virtual auditory landmark is provided. These preliminary results showed that the presence of virtual auditory landmarks did not impair the precision in a self-motion discrimination task, suggesting that the combination of the 3DTI Toolkit and the RT-Chair in an experimental setting is feasible for both sighted and visually impaired people. Interestingly, despite the large inter-individual variability, Fig. 4 shows

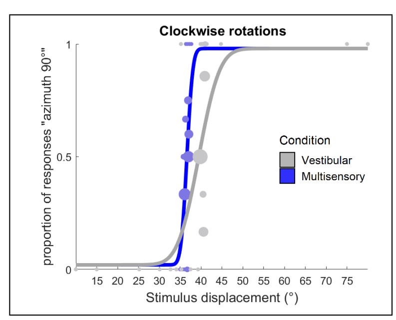

Fig. 3: Example psychometric fits. Individual visually impaired subject data from the Vestibular-only (gray line and shaded gray dots) and Multisensory (blue line and shaded blue dots) conditions, for clockwise rotations. The size of dots is proportional to the number of presentations for that particular stimulus displacement.

that for the visually impaired group there is a trend to decrease the variability in Multisensory condition, i.e., to increase the precision, becoming more similar to sighted group's performance. However, we tested the performance of a heterogeneous and small sample of participants: future studies will aim to homogenize and enlarge the sample of visually impaired people to investigate whether the trend of increasing precision will be confirmed. Since visually impaired people necessarily rely on auditory information during spatial orientation and navigation, more precise use of auditory landmarks than in sighted is expected. The onset of visual impairment may have a role in the ability to orient and move through space with auditory landmarks. Along these lines, it will be studied the orientation ability with auditory landmarks in people grouped by different onsets of the visual impairment. Previous literature claimed that spatial abilities in congenital blind individuals are more impaired than in people who develop blindness later in life because of crucial role of vision in the early years of life [18, 19]. Further studies will test the synchronization of motion stimuli with continuous auditory cues, to increase the sensation of self-motion provided by the auditory landmarks. In addition, future investigations on the neural correlates of audio-vestibular integration (e.g., using electroencephalography) will help elucidate the underlying mechanisms of this process.

IV. Conclusions

This preliminary study allowed us to test a novel experimental procedure that involved a tool for acoustic virtual reality, the 3DTI Toolkit, and a motion platform, the RT-Chair, both in sighted and visually impaired participants. On the one hand, the 3DTI Toolkit allows building flexible and immersive three-dimensional soundscape with flexible number, distance, and position of the sound sources, using simple binaural headphones as a playback device. On the other hand, the RT-Chair allows the investigation of a broad range of movements with a user-friendly Matlab interface. Overall, this pilot study revealed the successful use of a new combination of simulation tools to investigate self-motion perception in healthy and clinical populations. This promising technique may help to investigate multisensory perception and implement easily new rehabilitation procedures, in which the auditory-vestibular interaction may improve spatial representation abilities in visually impaired people.

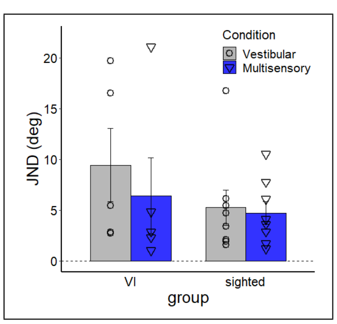

Fig. 4: JND values for visually impaired (VI) and sighted participants in Vestibular-only (grey) and Multisensory conditions (blue). Error bars represent standard error of the means. Individual data are represented by circles and inverted triangles for Vestibular-only and Multisensory conditions, respectively. Note that the higher the JND bar, the lower the precision.

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