Echo perception of normal hearing and cochlear implant subjects

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1 Introduction

The Simulated Open-Field Environment (SOFE) uses independently controlled loudspeakers in an anechoic chamber to simulate realistic auditory scenes with sources and echoes. Unlike virtual environments based on Head Related Transfer Functions, these stimuli are heard without the encumbrance of earphones, allowing easy comparisons between subjects with normal hearing (NH), hearings aids (HAs), and cochlear implants (CIs). Matlab based software allows parallel control of 48 auditory channels with on-the-fly speaker equalization, generation of stimuli, and experimental control including control of visual scenes in a separate visual renderer.

First experiments involved the development of a adjustment method for echo threshold determination. Subjects change the delay time between source and echo by turning a trackball. This offers the possibility to interactively explore situations with one or two sounds heard, thereby defining the threshold in-between. A normal hearing (NH) subject showed higher echo thresholds of clicks when both clicks came from the same direction suggesting less echo suppression in the spatially separated case. Echo thresholds appeared to be independent of source direction. Echo thresholds of a bilateral CI subject were similar to the ones of the NH subject for clicks. Monaural thresholds were higher for sources on the contralateral side and echoes on the CI-side.

2 Implementation of the SOFE

The SOFE consists of an arrangement of 48 loudspeakers mounted at ear level in an array surrounding the subject seated in the anechoic chamber (figure 1). Because the speakers are mounted along the walls of a rectangular anechoic chamber, the distance from speaker to subject is direction dependent. Using FIR-filters all speakers are equalized at the subject's head position to ±0.7 dB in 300 Hz - 10 kHz and a time/phase error of a few μsec, which cancels the between-speaker differences due to distance. Digital sound signals are delivered from a PC-type computer to a 48-channel D/A-converter (MOTU Audio 24 I/O, 24 bit/96 kHz). Analog signals are amplified (Crown D-75) before delivered to the speakers.

A high resolution video projector is mounted behind the subject to project visual scenes in future experiments (figure 1). The visual projection field of ±40° allows for an implementation of the *Pro De Po*-method for localization studies. With this method subjects move a visible object (light spot, dog, car, etc.) from an initial position to the apparent position of the auditory object by turning a trackball. Due to the indirect nature of the procedure the subject enters only relative directional information and proprioceptive bias effects are minimized [4]. The visual environment runs on a separate PC and it is controlled via udp-messages over the network.

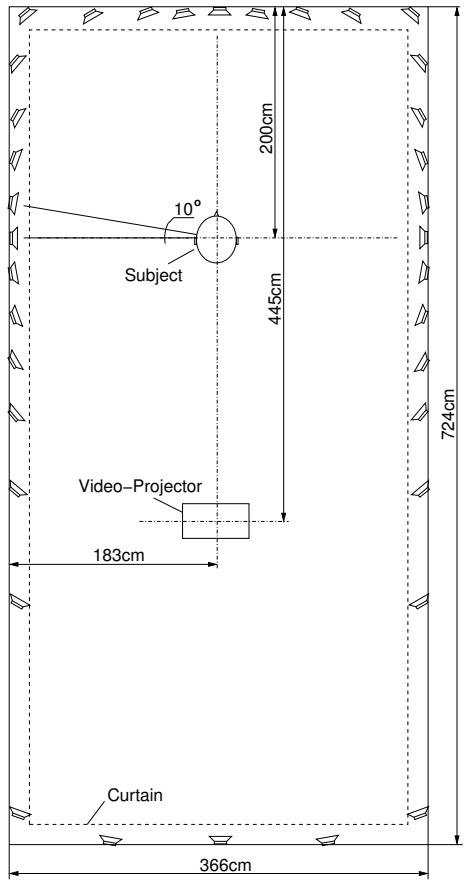

Figure 1: SOFE-apparatus in the anechoic chamber.

The trackball information is integrated over 100 ms on another PC and then sent via udp to the sound and the visual rendering PCs. All experimental control is done from Matlab on the sound-PC. Matlab is also used to generate sound signals, to equalize the speaker-signals on-the-fly, and to play sounds in parallel on up to 48 channels. This way sources and echoes can be played from several directions concurrently.

3 Adjusting the Echo-Threshold

To investigate the impact of echoes on the perception of sounds with CIs, a first study aims at finding the echo-threshold. The echo-threshold is defined as the threshold at which the echo becomes audible as a separate auditory object, whereas the presence of the second sound can be detected with a much lower threshold, the masked thresh-

old [1, pg. 224ff]. To directly study the echo-threshold, subjects are often asked to respond with 'one' or 'two' sounds heard in a single-interval procedure in which delay time and/or level for source and echo are adopted. When we implemented a discrimination-procedure for this task it appeared difficult to carry out as subjects required a certain amount of training to clearly distinguish the conditions 'one' or 'two' sounds heard as there appears to be a large 'gray'-region in-between these two conditions.

To overcome this problem a new method was developed which is based on an adjustment procedure. Subjects adjust the delay time between source and echo interactively by turning a trackball while levels are kept constant. The trackball-information is added linearly to the logarithm of delay time which leads to a higher sensitivity at small delay times. Stimuli are repeated with changing inter-stimulus interval to reduce adaptation effects and to help the separation into source-and-echo pairs. By using the adjustment method subjects can experience quickly and interactively the two distinct situations 'one' and 'two' sounds heard to later find the threshold in-between.

4 Subjects and Sounds

Echo thresholds were measured by means of the adjustment method of section 3 for a normal hearing (NH) subject (female, 28 years) and a bilateral CI subject (male, 52 years, congenital hearing impairment, HL>95 dB PTA, bilat. HAs throughout life, 1st CI for 2.5 years, 2nd CI for 0.9 years, both CIs are Advanced Bionics HiRes Auria at high rate). Test sound was a one sample click, band-limited by the speaker equalization to 300 Hz - 10 kHz with a level of 60 dB SPL, time constant 'impulse'. Level was roved between adjustments within ±6 dB. For the NH-subject 5 threshold measures were taken for sources at 0, 45, 90, 135, 180, 225, 270, and 315° accompanied by echoes of same level from either the source direction or locations ±90° away from the source. The CI subject conducted 5 trials each for the source-echo combinations $+45/-45°$ and $-45/+45°$ with both CIs and the 'better' CI on the right side.

5 Results and Discussion

Echo thresholds of the NH subject range between 2-4 ms relatively independent of source direction (figure 2). Binaural cues seem to play a minor role: the thresholds are identical for the source at +45° with echo from -45° (90° left, maximal binaural cues) compared to the situation with echo from +135° (front/back inversed to +45°, few binaural cues). The independency of thresholds from binaural information could be explained by an threshold-criterion based on gap-detection. Except for frontal sources the thresholds tend to be larger for co-located echoes than spatially separated echoes, i.e. for a spatial separation lower thresholds are obtained. This speaks against a monaural gap-detection criterion, and it suggests that a process similar to spatial unmasking occurs instead of spatial echo suppression [1].

The echo thresholds of the CI subject are comparable to the ones of the NH subject (figure 3). In a separate

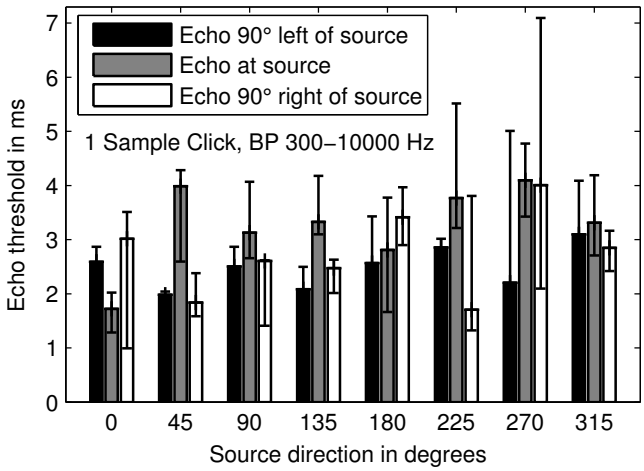

Figure 2: Adjusted echo thresholds for a normal hearing subject for co-located and spatially separated positions by 90° of echo and source in 360° space.

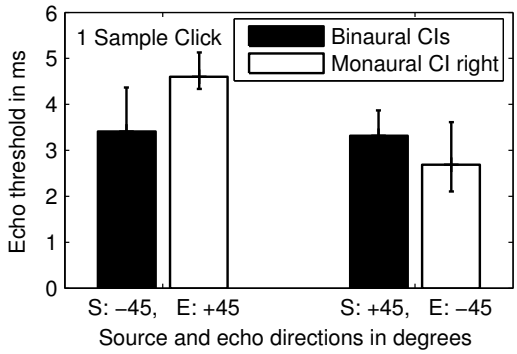

Figure 3: Adjusted echo thresholds for CI subject using bilateral CIs (dark bars) and the better single CI (bright bars).

study the CI subject showed coarse localization ability in 360° space using both CIs with a rms-error of 26.6° after correction for front/back reversals. As evaluation of binaural cues seems impaired with CIs, the identical results of the CI and the NH subjects could be explained by gap-detection. Gap-detection thresholds can reach normal values with CIs [2]. Monaural thresholds were higher for sources on the contralateral side and echoes on the CI-side. This is counter-intuitive, as forward masking is usually more pronounced than backward masking and the head-shadow effect reduces the level of the source compared to the echo in this condition. Further studies will be necessary to explain the results. In comparison, hearing impaired subjects might show elevated echo thresholds [3].

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