A New Method for Localization Studies

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Summary
Many scientific studies investigate and technical applications use the acoustical localization in the field of vision. Therefore it is suitable to display the perceived auditory direction by a light point. In formerly known methods subjects use a hand-held light pointer or a pointer mounted on a revolvable axle in front of them. However, the subject's motor system or the optical parallax may influence the results of those techniques. The calibration of the system and data logging also turn out to be difficult. The proposed new method utilizes a laser pointer with a deflection unit instead, which is controlled by a computer. Subjects enter the perceived sound direction with a trackball. The laser spot moves according to the rotation of the ball smoothly on a defined track. A complicated mechanical calibration can be avoided by calibrating the deflection unit by a computer. The intuitive experimental operation and the high resolution of the system make this method particularly suitable for localization research in audiology, psychoacoustics, and virtual acoustics. The symmetric, bimodal outlay of the experimental task reduces interaction effects between different modalities. Localization results for variable and fixed initial laser position obtained by this method are presented and compared to results acquired by other methods.

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1. Introduction

Acoustical directional displays in real and virtual environments gain in importance by the introduction of multimedia in many fields of everyday life. Applications range from teleconferencing systems over computer games to user interfaces in control and surveillance systems. The multitude of new applications is accompanied by an increased demand of knowledge about auditory localization in the field of psychoacoustics and audiology or within the scope of a specific application. All methods for the investigation of auditory localization require the subject to specify the perceived auditory direction. Known methods compare two directions, i.e. detect the perceived difference between two directions, or directly point to the direction [1]. Besides the information about the mean apparent direction the directional scatter is of interest for the acuity of localization. To provide information on the uncertainty of localization the testing method must add less variance to the responses than the sensory task. The response bias introduced by the method should be small and a quantization of the results should be omitted. The method should be intuitively to handle and easy to learn for the subject. A computerized data collection is a prerequisite for a high data acquisition rate and a fast evaluation of the responses.

Several methods in ego- and exocentric space have been proposed so far. A simple exocentric method requires the subject to mark the perceived sound position in a coordinate system on a piece of paper [2]. Using this method distance information can also be assessed. A projectional pointer method in an exocentric coordinate system is the GELP-method or "Bochum Sphere", where subjects indicate the apparent direction on a sphere [3, 4]. This comfortable method covers the whole space and provides fast responses. However, Djelani et al. [5] point out that the GELP-technique requires some training and the projection leads to systematic errors in connection with a reduction in accuracy. If pointing in a non-body-centered system is not favoured, pointer methods in the egocentric coordinate system should be chosen. Hand-, head- and eye-pointing are extensively studied (hand [5, 6]), (head [5, 7, 8, 9, 10]), (eye [11, 12, 13, 14]). These natural and intuitive methods achieve a high accuracy in frontal direction despite the use of the motor system for indication of the auditory direction. At lateral positions, strong systematic errors occur due to limitations of the motor act and intersensory projections. The methods are thus limited mainly to the frontal sector. Further methods involve the naming of speaker numbers or the angle. The latter is referred to as "absolute judgement technique" and covers the whole space but requires extensive training [15, 16]. The precision of the visual system allows visual pointing to acoustic targets [17]. In order to minimize errors introduced by the mapping of auditive coordinates to visual or motorical coordinates acoustic pointers can be introduced [18]. Using these pointers, care must be taken that subjects use directional instead of timbral cues as a decision variable for the adjustment of the pointer. However, as the test-stimuli and pointer directions undergo the same coordinate transformation from acoustic (physical, external) to auditive (perceived) directions, a relative rather than absolute direction will be displayed in terms of a minimum audible angle [19]. An unimodal advantage is given if the pointer input-interface allows no direct relation to visual or motorical coordinates.

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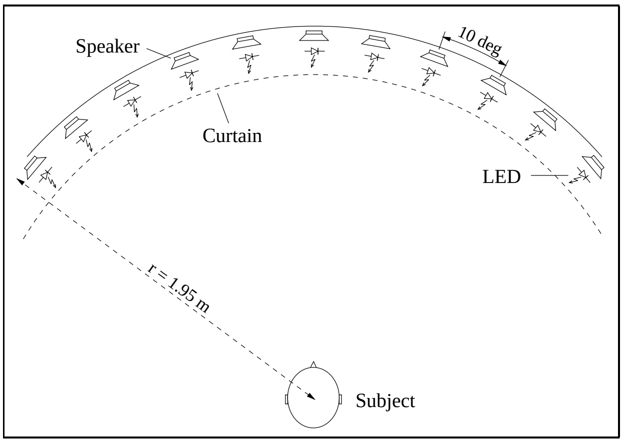

Figure 1. Apparatus.

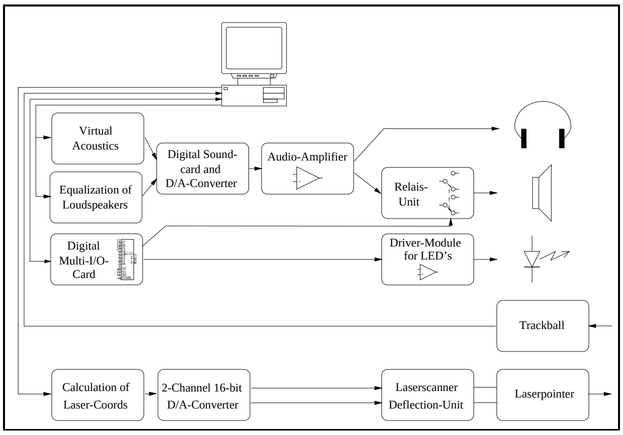

Figure 2. Block diagram of the experimental setup.

In this paper a new method for the investigation of localization in the field of vision is proposed which utilizes a laser spot for displaying the perceived auditory direction. The position of the laser spot is adjusted by the subject with a trackball. The laser spot moves according to the rotation of the ball smoothly on a defined track utilizing a laser scanner. As the trackball permits positioning in two dimensions, the method can be adopted for investigations in the horizontal and vertical plane. This fast and accurate method can be intuitively operated, making a wide range of applications from audiology to virtual acoustics possible. Moreover, by pointing using the trackball from an egocentric frame of reference, a decoupling from the motorical system is achieved resulting in a bimodal pointer method. The initial position of the laser spot can be set arbitrarily by the experimenter trial by trial. This way subjects loose the perception of their position in the completely darkened surrounding space and thus need to point relatively to the perceived direction. The system can be calibrated easily by fixed position points as a computer does the coordinate transformation between the laser and the subject's coordinate system. This relative calibration against the speaker positions assures a remarkably high accuracy of the visual directional display. The computer control permits fully automated experimental runs and an instant evaluation of the results.

2. Apparatus and Experimental Setup

The apparatus is installed in an anechoic chamber (dimensions L * W * H = 7.5 m * 4.2 m * 2.8 m), which is completely darkened during the experiments. Eleven identical loudspeakers (chassis Nokia 49102 10121/2 in a closed cabinet) are mounted on a circular tube in a distance of 1.95 m from the center of the head of the subject at ear level. The speakers span an angle of 50 deg left to 50 deg right with a spacing of 10 deg. Figure 1 shows the apparatus. The frequency response of each speaker is individually equalized by a 128-point linear-phase FIR-filter (sampling frequency $f_s = 44100$ Hz) to 125 Hz – 20 kHz in ± 2.5 dB at the subject's head position. Light emitting diodes (LEDs) are mounted in a distance of 10 cm concentric in front of each speaker. The speakers are switched by a custom-made relay-unit utilizing high-speed relays with a switching time smaller than 2 ms (NAIS Matsushita TK 1). A driver-unit for the LEDs, a power-supply for the laser and the relay-unit are controlled by a TTL-Multi-I/O-Card (Decision-Computer 82192V) installed in a PC-type computer. Figure 2 shows a block diagram of the experimental setup. Additionally, a 2-channel 16-bit digital-to-analog-converter-card is used (Kolter Electronic DAC 16 dual) which controls two laser-scanner galvanometers (Cambridge Technology CT 6800 HP, closed-loop) by a driver unit. The position-repeatability of the galvanometers is better than 0.0011 deg (manufacturer information). The laser beam is deflected by the galvanometers in x- and y-direction and projects a laser spot onto a curtain in front of the loudspeakers. The curtain is opaque for the subject's gaze but acoustically transparent and translucent for the light of the LEDs. The laser and the LED spot are of equal color (635 nm), brightness (1 mW laser) and width (5 mm). The calibration of the x/y-deflection of the laser beam is done by adjusting the laser spot to the position of the LED in front of each speaker. This way the pointer coordinate system is aligned to all speaker positions, nonlinear effects of the galvanometer or its drivers are cancelled out and a maximum pointing accuracy relative to the speaker coordinate system is achieved. The repetition accuracy at the speaker positions is 0.03 deg, reflecting the deviation between pointing and presentation coordinate system. The precision of the absolute positions of the speakers determines the precision and linearity of the system to about 0.2 deg.

The projected laser spot can be moved smoothly according to the rotation of the trackball on a horizontal track within ± 70 deg in front of the speakers. The computer performs the coordinate transformation between the angle of the laser spot seen by the subject and the deflection of the laser beam using the calibration data. This coordinate transformation also allows for the position of the laser scanner being out of the center of the projection cylinder.

As the system utilizes a deflection unit in two dimensions it could be extended for investigations in the vertical plane by exchanging the projection cylinder with a sphere and introducing calibration points at different elevations. Additionally, the coordinate transformation would have to be substituted by two- instead of one-dimensional spline interpolation.

Sound reproduction is done as follows: After the filtering of the sound for the equalization of the speakers or for virtual acoustics, the digital sound data are written out through a digital soundcard (Sek'd Prodif 32) to a D/A-converter (DAT Sony DTC 57ES). The speaker signal is amplified (amplifier Sansui AU-X 201i) and calibrated with a voltmeter (B&K 2409) before reaching the initially described switching unit. The experimental procedure is controlled by a Matlab routine with the help of customized interface software for the experimental setup.

3. Method and Subjects

In a localization experiment the subject is placed in the center of the speaker array on a chair. The head is stabilized by a head rest and subjects are instructed not to move their head. The subjects' experimental operation and the fixation of the head is monitored through an infrared camera. During all localization tasks head movements were not detected by the experimenter in the present experiments. In the beginning of an experiment a light appears straight ahead for five seconds in the completely darkened anechoic chamber to align the head to the frontal direction. After a pause of 500 ms a target sound is presented in a randomly selected angle, i.e. played from a certain speaker. The angles for presentation are distributed from 50 deg left to 50 deg right in 10 deg intervals. Gaussian white noise (125 Hz - 20 kHz, continuous sound pressure level 60 dB SPL) serves as a target sound which is divided into 5 pulses (pulse duration 30 ms, duration of pauses 70 ms, 3 ms Gaussian shaped slopes). After a pause of 500 ms a light spot appears under a randomly chosen initial angle in the range of ± 20 deg around the presented physical angle of the target sound. The subject's task is to adjust the light spot to the perceived direction of sound incidence. By pressing one of the trackball buttons the subject acknowledges the indicated direction and the light spot disappears. The three trackball buttons might be used to code the perceived position of the sound source as in front, inside the head or behind of the subject. After a pause of 500 ms the next trial starts with the presentation of the target sound under a different angle. After testing each of the eleven directions the fixation LED straight ahead lights up for five seconds to allow subjects a short pause. Subjects received no feedback about their responses and conducted no training sessions except seven single trials without feedback in the beginning of each session for accommodation. The experiment yields quasi-continuously distributed data of the adjusted light angles. A localization experiment as described with ten repetitions of all eleven angles of sound incidence (110 trials) takes about nine minutes.

Exp. 1: Twelve subjects, age 23-28, two female, ten male, participated voluntarily in the localization experiment with variable initial laser direction and conducted 20 trials per direction of sound incidence in two sessions of ten trials. The Békésy audiometric method showed normal threshold in quiet within ± 20 dB in 20 Hz-16 kHz for all subjects. Three subjects, including the author, were members of the institute, eight subjects were students, and one subject was invited to the experiments from outside the university. Two of the subjects had previous knowledge of the positions of the speakers, further four subjects had knowledge of a discrete distribution of the speakers.

Exp. 2: To estimate the influence of the initial laser position a second experiment was conducted. The procedure and the stimuli of exp. 2 were identical to exp. 1, except for the fact that the initial laser position in each trial was not varied within ± 20 deg around the sound direction but was fixed at 0 deg in front. Eight of the subjects of exp. 1, two female, six male, age 23-28, participated in the second experiment and conducted ten trials per sound direction in one session.

Exp. 3: A third experiment was conducted with seven of the subjects of exp. 1, one female, six male, age 24-27 to assess the influence of the visual pointing accuracy on the localization method. Therefore the procedure of exp. 3 was kept identical to exp. 1, but remembered visual targets instead of sound directions were indicated. The LED's in front of each speaker served as visual targets. Likewise in exp. 1, in each trial a LED in a randomly selected angle lit up for 500 ms and after a 500 ms pause the adjustable laser spot appeared within ± 20 deg around the previously presented direction. The seven subjects conducted ten trials for each of the eleven directions in one session.

4. Results and Discussion

Figure 3 displays the deviation of the indicated from the stimulus direction obtained in two localization experiments with wide-band noise pulses, exp. 1 (o) and 2 ($*$), and with pointing to remembered visual targets, exp. 3 ($\diamond$). The data are presented as medians of individual medians and medians of individual quartiles. The results of all experiments show a high agreement between presented and localized direction and a small variability in the displayed direction.

The standard localization experiment, exp. 1, using a laser spot which is randomized in initial position trial by trial, yields localized directions which are indicated about 1.5 deg right of the presented direction and slightly overestimated for lateral angles. The sound source at 50 deg right was localized at 54.9 deg, whereas the source at -50 deg left was judged to -51.3 deg. The lateral spread of the indicated direction is reflected in the linear factor of 1.05 of a least-squares line-fit to the median localization responses. The median distance of the median indicated from the presented direction is 1.6 deg, which represents the mean absolute error. The rank correlation coefficient according to Spearman for the signed distance of the median localized

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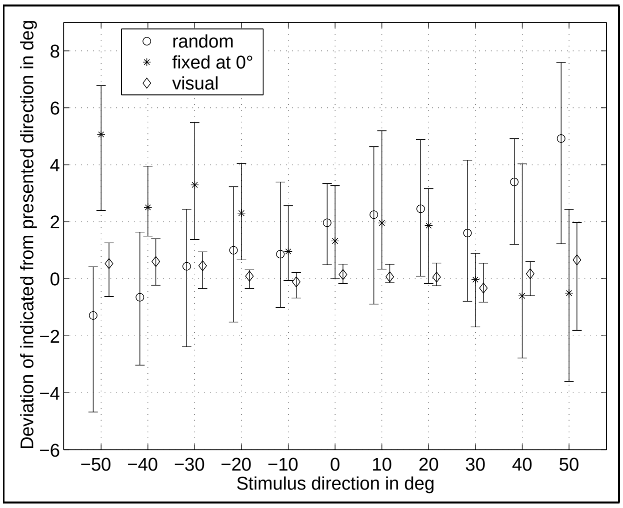

Figure 3. Medians and quartiles of results of localization experiments with wide-band noise pulses and visual stimuli given relative to stimulus position. Exp. 1 (o) : Random initial angle of laser pointer position within ± 20 deg, Exp. 2 (∗) : Fixed initial laser position of ± 0 deg in front of the subjects, Exp. 3 (◇) : Pointing to remembered visual targets; random initial laser spot position. Angles 50 deg left to 50 deg right were tested in 10 deg increments. The data of Exp. 1 and 3 are shifted horizontally for better distinction.

and presented directions also displays this relationship by a highly significant correlation with the presented direction (r_s = 0.94, p = 0.000022). The median upper (lower) quartile of the individual localization responses, an indication of the average intra-subject variance and the dispersion of localization responses, is 2.3 deg (-2.4 deg).

Exp. 2 was conducted to assess the influence of the initial laser spot position. The results show an underestimation of the lateral angle and a decrease in variance of the data compared to exp. 1. The most lateral sound sources at ± 50 deg were estimated to -44.9 deg and 49,5 deg. The underestimation of lateral directions can also be expressed by a linear fit of the medians to the presented directions: the linear coefficient is 0.95 whereas the additive constant is 1.6 deg (right). The correlation of the deviation of the indicated from the presented direction with the stimulus direction is highly significant and negative, i.e. a positive lateral shift in the presented angle results in a negative deviation, an underestimation of the angle (Spearmans rank correlation coefficient r_s = -0.90, p = 0.00016). The right-shift of all indicated directions against the presented ones is equal to exp. 1. Similar shifts were also observed by Blauert, who estimates the right-shift to 1 deg [1, p. 41]. The absolute error is 1.9 deg. Besides the underestimation effect a decrease in variation of the responses is observed with fixed laser spot position. The median upper (lower) quartile of the responses is 1.7 deg (-1.7 deg) and about 0.6 deg smaller than with variable laser spot position.

The localization results using this method coincide with results previously obtained by different methods or even surpass previous results. Makous and Middlebrooks [9] observed azimuthal errors of 2 deg in the front and 9 deg at 60 deg lateral in a 2-dimensional localization task using head pointing after substantial training sessions. Bronkhorst [8] observed 3 deg of mean absolute azimuthal error in a similar task, whereas this study found the absolute error to be 1.6 deg (exp. 1). The errors in eye pointing usually turn out to be greater than with head pointing: Frens and van Opstal [11] as well as Heuermann and Colonius [14] observed an azimuthal error of about 6-8 deg in the range of ± 30 deg. The first study also reported an underestimation with a linear factor of 0.95. Many other studies reported only 2-dimensional errors without addressing the azimuthal component [5, 15, 16]. The smaller errors in the present study might be attributed to the bimodal and symmetrical outlay of the laser-pointing experiment as well as the impact of the high accuracy of the visual system on the direct comparison task with auditory directions. The proprioceptive interaction in head pointing leads to a strong increase in error with lateral position which is not observed to this amount in the laser pointing experiment [9]. The azimuthal standard deviations observed with head pointing range from 2 deg in the front to 7 deg at 60 deg lateral [9]. Bronkhorst [8] found a mean azimuthal variability of 5 deg. The better variability results in the present study might be also attributed to the bimodal advantage, whereas parts of the improvement might result from the data-analysis method based on quartiles and from the one-dimensional experimental task. The superiority of the fixed laser against the variable laser condition (exp. 1 vs. 2) in terms of variability is due to the supply of information of the subject's position in the surrounding space. A variation of the initial laser spot position suppresses the buildup of usable information for this case. The auditory direction can be evaluated in the fixed condition relative to the frontal direction which reduces the uncertainty in the display. This was also reported by the subjects. One further methodical difference between the fixed and variable method should be noted. The mainly symmetric influence of the laser position on the indicated sound direction in the variable case (exp. 1) is changed in the fixed case to a one-sided influence from the frontal, inner position. Thus, the indication of different lateral positions is not methodically equal as the mean traversed angle differs with position and memory effects might influence the results. However, other localization methods, e.g. head pointing, cannot control the initial position or reduce the described methodical influence.

The data on auditory localization obtained by a visual pointer can only be correctly interpreted if the effect of the visual pointer is discussed. Exp. 3 was designed in the same way as the standard localization experiment, exp. 1, but with the difference of pointing to remembered *visual* instead of auditory targets. As in exp. 1, the initial laser spot position was varied to yield comparative data. Figure 3 displays the results in comparison to the auditory localization experiments. It can be seen that the quartiles are substantially smaller for visual targets and that no deviation from the presented direction occurs. The indicated directions were tested against the presented directions for equality and no significant deviation was observed (Wilcoxon signed rank test α-corrected for 11 directions, not significant at 1%). This is also reflected in the median absolute error of 0.2 deg. Further, the median upper (lower) quartile of the indicated directions is 0.5 deg (-0.6 deg) and thus about 4.6 (3.4) times, or 1.8 deg (1.2 deg), smaller than in auditory experiment 1 (exp. 2). When comparing this accuracy with the minimum observable auditory angle of about 1 deg [1, 19] it becomes evident that the visual pointing accuracy itself is adequate for pointing to auditory targets. The exact reproduction of visual positions with a movable pointer of variable initial position requires a mechanism of exact memorization of the perceived positions as the medians are not shifted significantly. Existing interference effects between the memorized and the pointer position are reduced by the statistically symmetrical, two-sided scattering of the initial laser positions. Thus, these interference effects rather result in an slight increase in variance than in a shift of the indicated position. The comparison of the perceived visual pointer position with the auditory coordinates, however, introduces some variance which is difficult to measure. This coordinate mapping from auditory coordinates to directions in other modalities is inherent to all pointer methods as they require the subject to compare both directions. The main benefit in this regard of the new method in contrast to many other formerly known methods is that it involves only two modalities, auditory and visual. As no motorical interactions occur and visual interactions are kept at a minimum, it can be assumed that the interference from other than auditory modalities is relatively low with the new method.

Although this method can be used only in the field of vision, the high accuracy of the method and the possibility of evaluating the variation in the responses give this method a wide range of applications. Besides applications in virtual acoustics and psychoacoustics, the intuitive and fast handling of the apparatus and method make this method particularly suitable for localization research in audiology [20]. In localization studies with hearing impaired subjects, the initial direction of the laser spot should not vary around the presented sound direction but should be straight ahead. Thus it can be assured that the variability in the adjusted direction is a measure for the accuracy in localization. As hearing impaired subjects gain more information from monaural level differences between the trials as normal hearing subjects, the level should be randomized in each trial. Besides that the mean level can be increased to 70 dB SPL.

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