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Sound localization, sound lateralization and binaural masking level differences in young normal-hearing children

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Abstract

Objectives: In this study, procedures for measuring sound localization, sound lateralization and binaural masking level differences in young children were developed. Sensitivity for these tasks was assessed in large groups of children between 4 and 9 years of age to investigate potential developmental trends.

Design: Sound localization was measured in the sound field, with a broadband telephone signal presented from one of nine loudspeakers positioned in the frontal horizontal field. A group of 33 normal-hearing children between 4 and 6 years of age and 5 normal-hearing adults took part in this experiment. Sound lateralization based on interaural time differences was measured with headphones in 49 normal-hearing children between 4 and 9 years of age and in 16 normal-hearing adults. A low frequency stimulus containing harmonics 2 to 5 from a click train with a rate of 160 Hz was used. In the binaural masking level difference (BMLD) test the same filtered click train was presented diotically or time/phase-delayed in a wideband (200 Hz – 1000 Hz) frozen noise to 23 normal-hearing children between 4 and 6 years of age and 10 adults. For comparison with literature, additional measurements with a 500-Hz sinusoid were done with adults. All tasks were adapted to the interest and attention span of young children.

Results: BMLD values were similar for 4 year olds, 5 year olds and adults. Concerning sound lateralization, a small but significant difference with the adults existed, but no age effects were apparent in the 4- to 9-year-old group. Children of 5 years of age did not perform significantly different from adults on the sound localization task, but mean absolute errors were higher for the 4 year olds. Overall, the variation was relatively large in the 4-year-old group, with some of them performing at adult level, even in the localization task.

Conclusions: The results of this study show that the modified procedures are suitable for testing children from the age of 4. Furthermore, it seems that some binaural hearing capacities are fairly well acquired at this young age. Several observations lead to the hypothesis that differences, on sound localization or lateralization, between 4 and 5 year olds or between children and adults, were primarily attributable to factors other than hearing skills, like task comprehension, attention and testing conditions. Possibly a development exists in other binaural hearing capacities, which require more dynamic or more central processes.

Keywords: binaural hearing, children, sound localization, sound lateralization, binaural masking level differences

Introduction

Hearing with two ears has several advantages compared to hearing with only one ear. These advantages can be attributed to three effects: a summation effect or an amplification of sounds in the brain due to stimulation of both ears, a head shadow effect or the ability to listen with the ear with the most favourable signal-to-noise ratio (SNR), and a squelch effect or the improvement in internal SNR due to interaural comparisons (Dillon, 2001). Combining stimuli arriving at both ears makes it possible to locate sounds in the environment and to better detect signals or understand speech in noise when the sound sources are separated spatially. The functions underlying these capacities are usually referred to as 'binaural hearing'. Different tasks for measuring binaural hearing capacities exist, such as sound localization in free field, sound lateralization under headphones, the binaural masking level difference test and the binaural intelligibility level difference test. These have been administered to normal-hearing and hearing-impaired adults (Bronkhorst and Plomp, 1992; Gabriel, Koehnke, and Colburn, 1992; Hausler, Colburn, and Marr, 1983; Klumpp and Eady, 1956; Mills, 1958; Van den Bogaert, Klasen, Moonen et al., 2006; van Hoesel and Tyler, 2003; Yost and Dolan, 1978). In order to measure binaural hearing in young children, it is necessary to deal with methodological problems. Adult procedures are not suitable for testing young children, as they usually require long test sessions, high levels of concentration and abstract responses. However, it is not easy to modify procedures without losing accuracy. Perceptual data on normal-hearing children exist, but are often not comparable due to the use of different procedures. In addition, there is a lack of data on preschoolers. In the present study three procedures for measuring binaural hearing, namely sound localization in the sound field, sound lateralization based on interaural time differences (ITDs)

and binaural masking level differences, were modified to the interest and attention span of young children.

Sound localization in free field is an integral measure of binaural hearing, as it assesses the ability to use different interaural cues, both differences in arrival time of the sound at both ears (interaural time differences or ITD, ranging between 0 μsec and 700 μsec) and differences in amplitude of the sound at both ears (interaural level differences or ILD, ranging between 0 dB and 30 dB). In the horizontal plane, the localization of low frequency sounds is based on ITD, whereas mainly ILDs are used to localize high frequency sounds (Moore, 1997). With a broadband signal both cues can be used by the listener. Some researchers examined sound lateralization or left/right discrimination with infants in free field, by means of head-turning responses. In a lateralization experiment the limits of spatial acuity, often expressed as the minimum audible angle (MAA), are usually determined around the midline (0°). Typical adult MAAs for this direction range between 1° and 3°, depending on the stimulus type (Hausler, Colburn, and Marr, 1983; Litovsky, 1997; Mills, 1958; Senn, Kompis, Vischer et al., 2005). For infants of respectively 20, 24-27 and 48-52 weeks old MAAs of 20°, 12-19° and 9-10° have been determined with broadband stimuli, while children of only 18 months seem to discriminate sounds that are separated by 4° to 6° or less (Ashmead, Clifton, and Perris, 1987; Ashmead, Davis, Whalen et al., 1991; Morrongiello, 1988). In a study of Litovsky et al. (1997) the MAA of 5-year-old children, namely 2°, did not differ significantly from the adult value of 1°. Their subjects responded by pointing to the left or the right once the sound shifted away from midline. Although MAA data vary across studies due to different procedures, this summary seems to show a decrease in the MAA up to 5 years of age. In the lateral field infants show a poorer resolution of auditory space than in the frontal field, just like adults (Mills, 1958), with MAAs of 17°, 14° and 10° at 6, 12 and 18 months, respectively (Morrongiello and Rocca, 1990). These are very

valuable data about the limits of spatial acuity. However, because the MAA involves a discrimination task, it does not reflect absolute localization accuracy, i.e. determining precisely where a sound is coming from. Localization accuracy is measured in an identification task, in which the listener has to indicate the precise location of a sound source. The performance is often expressed as a root mean square (RMS) error or mean absolute error (MAE). The localization accuracy of normal-hearing adults strongly depends on the stimulus type. With broadband signals RMS errors of 6° to 10° (Lorenzi, Gatehouse, and Lever, 1999b; Van den Bogaert, Klasen, Moonen et al., 2006) and MAEs of 4° to 5° (Hofman and Van Opstal, 1998; Makous and Middlebrooks, 1990) have been measured. Narrowband signals are harder to localize, with RMS/MAE values between 10° and 15° for low frequencies and higher than 15° for high frequencies (Good and Gilkey, 1996; Stevens and Newman, 1934; Van den Bogaert, Klasen, Moonen et al., 2006). Bess et al. (1986) investigated sound localization in children between 6 and 13 years of age. However, their error index is not comparable with adult RMS/MAE data. The literature does not report on preschoolers, but Morrongiello and Rocca (1987) determined localization errors of 16° to 6° for infants aged 6 to 18 months, using head-turning responses on click trains presented from one of ten loudspeakers in the frontal horizontal plane. These data seem to indicate that sound localization is at adult level at 18 months of age. However, the use of a head-turning method in an identification task is questionable. In the first experiment of the present study we modified the localization setup, used with adults in the work of Van den Bogaert et al. (2006), for testing young children.

In addition to binaural hearing in general, it is possible to study the processing of one separate cue, for instance the ITD. The just noticeable difference in ITD or ITD JND, is examined in a lateralization task with stimuli containing different ITDs and a 0-dB ILD, presented through headphones or insert phones. Adult ITD JNDs are subject to stimulus type, with a minimum

around 10 μsec, for a 1000-Hz pure tone or repeated clicks (Klumpp and Eady, 1956). Ashmead et al. (1991) recorded ITD JNDs of 50-75 μsec for a broadband stimulus in infants aged 16 to 28 weeks. While these data indicate that the processing of these binaural stimuli is already fairly accurate in infants, their values are significantly higher than the adult values reported in the literature. To our knowledge no data on preschool children have been reported. The second experiment in this paper describes the development and evaluation of an adaptive procedure for estimating the ITD JND in young children. Children responded by pointing to the perceived side of the stimulus instead of by turning their head. The use of a head-turning method can be problematic in a headphone experiment, as infants might not make directional responses to sounds that are not externalized, even if they are sensitive to the interaural cues.

The processing of time differences can also be investigated by means of binaural masking level differences (BMLD). The BMLD refers to the unmasking due to relative interaural differences between signal and masker. Detection thresholds in diotic (N_0S_0) and dichotic conditions have been measured in adults and children. The dichotic condition is often implemented by phase shifting (π) or time delaying (τ) the signal at one ear opposed to the other ear while keeping the noise identical (N_0S_π / N_0S_τ). The difference in threshold between the N_0S_0 and $N_0S\pi$ or N_0S_τ condition is called the BMLD. In normal-hearing adults unmasking effects up to 19 dB have been determined, depending on the type of the stimulus (Hall and Harvey, 1985; Hirsh, 1948; McFadden, 1966; Yost, 2000; Yost and Dolan, 1978). Nozza et al. (1988) reported BMLDs for the CV syllable /ba/ of 5.0 dB, 8.3 dB and 10.8 dB for infants of 7 and 8 months, preschoolers of 4 years of age, and adults, respectively. The authors attributed the difference between preschoolers and adults to differences in absolute sensitivity, as BMLDs are known to be larger at higher masker levels (McFadden, 1968). The 4- to 12-year-old children in the study of Sweetow and Reddell (1978) had a mean BMLD of 6.9 dB for a 500-Hz sinusoid in a white noise

masker, which was not significantly different from the adult value of 8.0 dB. Variation with age in the children group was not analyzed, just like in the study of Roush and Tait (1984), who obtained a mean BMLD of 12.2 dB for a 500-Hz sinusoid in a narrowband noise with 6- to 12-year-old children. In all these studies thresholds were obtained by means of a yes-no detection task, using visual reinforcement audiometry (VRA), play audiometry or standard audiometry. The yes-no paradigm, however, does not produce a criterion-free measure of detection or discrimination thresholds. Moreover, this paradigm suffers of more response bias because listeners tend to regard the decision outcomes ('yes, a signal' or 'no, no signal') as quite different in value. A forced-choice procedure, with equivalent decision outcomes (a signal in interval 1, 2 or 3), is therefore preferable in studies of sensory functions (Green and Swets, 1988). Hall et al. (1990) used a three-alternatives forced-choice procedure (3AFC) and obtained significant different BMLDs for 26 children between 4 and 9 years of age (12.9 dB) on the one hand and 10 adults (14.7 dB) on the other hand, with a 500-Hz sinusoid in a 300-Hz-wide masker. Their analyses indicated that the BMLD increased up to an age of about 5 or 6 years. Another study of the same group showed that the difference between children and adults is dependent on the masker bandwidth and that children perform more adult-like with larger bandwidths (Grose, Hall, and Dev, 1997). In these studies some age groups consisted of only one or two children. In our third experiment BMLDs were investigated with an adaptive 3AFC task in a large group of children in a restricted age range (4 to 6 years of age). Instead of a 500-Hz sinusoid, a 160-Hz click train was masked by a 1000-Hz-wide noise. These stimuli were chosen as more appropriate for testing cochlear-implanted subjects in the future.

In view of possible bilateral intervention of hearing-impaired children, it would be beneficial to know whether certain binaural hearing capacities are acquired early in childhood or whether a longer period of development is necessary. Anatomical and physiological studies

suggest that the binaural system might not be fully developed before puberty. Overall neuronal maturation as well as binaural neuronal maturation takes several years. The cortical depth and the cytoarchitectural organization of the auditory cortex are adult-like by 3 years of age, but myelinization of axons goes on until later childhood (Moore and Guan, 2001). After 5 years of age, mature axons begin to appear in cortical layers 2 and 3, and by 11 to 12 years of age their density is equivalent to that of young adults (Moore, 2002). Myelinization and increasing density of fibers might give rise to more accurate signal transmission and increasing complexity in cortical processing of auditory information with age (Eggermont and Ponton, 2003). Furst et al. (2004) believe that this might for instance improve the detectability of binaural components in the auditory brainstem responses. It is not clear however, whether these anatomical and physiological changes go together with a better performance on the binaural tasks we are considering. From the perceptual data summarized before it is difficult to draw solid conclusions. Data on preschoolers of different ages, obtained in a systematic way with adequate procedures, should provide a better insight into this matter.

This paper offers a description of new procedures for sound localization, sound lateralization with ITDs and binaural masking level differences with ITDs. All tasks were embedded in a game, test procedures were automated where possible and efforts were made to keep the test time as short as possible and to limit the cognitive demands. Large groups of normal-hearing children between 4 and 9 years of age were tested with the same procedures. Adult data were gathered with similar procedures. The results of these experiments enable us to draw some conclusions on the development of three binaural tasks during this period of childhood. Furthermore, these procedures should make it possible to assess binaural skills in bilaterally cochlear-implanted children in the future. Stimuli were chosen in that context.

Methods and Results

Most of the children in this study were recruited from neighbouring schools, others through personal connections. The lateralization and BMLD tasks were done in a quiet room at the children's school or home, the localization task was carried out in a sound-controlled room. All adult data were gathered in a sound-controlled room or booth. Testing was approved by the K.U.Leuven Medical Ethical Committee and was in accordance with the Declaration of Helsinki (1975). Subjects were paid for participating (adults) or received a small present (children).

Audiometry

Hearing thresholds were assessed in adults and children by means of standard audiometry or play audiometry, respectively, with A MADSEN Orbiter 922 audiometer or a portable MADSEN Midimate and TDH-39 headphones.

In adults, normal hearing was defined as hearing thresholds of 20 dB HL or better on all octave frequencies from 125 Hz to 8000 Hz. Children's thresholds were assessed at octave frequencies 250 Hz to 4000 Hz. Sometimes frequencies had to be omitted as tasks demanded a lot of concentration. Normal-hearing was confirmed in at least one low frequency (250 / 500 Hz) and one mid- to high frequency (1000 / 2000 / 4000 Hz). In children, 25 dB HL was taken as the normal-hearing boundary. Localization, lateralization and BMLD data were gathered in respectively 33, 49 and 23 normal-hearing children. Data of respectively 11, 9 and 12 children were discarded due to not reaching the abovementioned criterion. Because of time constraints no audiogram could be obtained from 10 children participating in the lateralization experiment.

Experiment 1: Sound Localization

A sound localization task with a broadband signal presented from one of nine loudspeakers was embedded in a telephone game. In this task interaural time cues, interaural level cues as well as spectral cues were available to the listener.

Materials and Methods

Subjects

A group of 33 normal-hearing children (13 boys, 20 girls; 4y (21), 5y (6), 6y (6)) performed the localization task. Additionally, 5 adults between 23 and 27 years of age (mean age of 24 years) were enrolled to have reference values of the localization capacity of adults in the specific setup used in our study.

Setup

For an illustration of the adult test setup the reader is referred to Van den Bogaert et al. (2006). The children setup is presented schematically in Figure 1. The localization tests were carried out in a standard office room with dimensions 6 m x 3 m x 3.5 m and a reverberation time, T60, of 0.54 sec, as determined for a speech-weighted noise spectrum. An array of nine single-cone loudspeakers with a cone diameter of 10 cm was positioned in the frontal horizontal plane at 1 m from the subject. Loudspeakers were spaced 15° apart, spanning the area from -60° to +60°. Each loudspeaker was connected to an electronic switchbox driven by a LYNXONE soundcard. The pc with software and soundcard as well as the switchbox were located in a control room adjacent to the test room. With adults, the test operator controlled the localization

test from the pc in the control room. A camera placed in front of the subject allowed for controlling the position of the subject and answers were passed on through a microphone. With children, a touch screen was placed in the test room and connected to the pc in the control room, such that the test operator was in the test room with the child. The whole test procedure was managed by the custom-made software "Advanced Localization Procedure" (ALP). Root mean square errors (RMS errors) and mean absolute errors (MAE) were calculated and stored automatically, together with confusion matrices.

Stimuli

A broadband signal, namely a 1 sec telephone ring, was used in our experiments such that both interaural time and interaural level cues could be used, as an integral measurement of binaural hearing. The telephone ring was cosine windowed with a rise and fall time of 50 msec (Van den Bogaert, Klasen, Moonen et al., 2006). One reason for choosing this particular signal was the convenient use in a localization game. Other added values of the telephone ring to a broadband noise are the presence of transients, which should make localization easier, and the fact that people are familiar with localizing telephone signals in their daily life. Litovsky et al. (2006) used spondaic words in their MAA experiment. The use of different words in each trial, however, increases stimulus uncertainty.

Test Protocol

Subjects were seated in the center of the array, facing the middle loudspeaker. The chair was elevated until subject's ears were at the level of the loudspeakers. Stimuli were presented at a level of 65 dB SPL, measured at the center of the array in absence of the subject's head, with an additional level roving of 5 dB (between -5 dB and 0 dB).

With adults, the test operator was seated in the control room and watched the subject through a camera. He presented a stimulus by clicking on a button. Subjects were instructed to look straight ahead during stimulus playback. They responded by saying aloud the number of the loudspeaker. The operator recorded the subject's response and no feedback was given.

With children, instead of numbers, pictures of different smurfs were used. An example of such a picture can be found in panel a of Figure 2. Pilot tests had shown that response bias was smaller for smurfs than for faces of different people, like a cook, policeman, little girl etc. Smurfs are similar to each other except for their attributes, which diminished the occurrence of a preference for one particular picture. Before testing the experimenter asked the child to name each smurf and that name was used throughout the experiment. Toy telephones were placed on top of each loudspeaker and the localization task was embedded in a telephone game. One test operator (Op1) was seated in front of the child and held a toy telephone for calling the smurfs. Children had to indicate which smurf was called, by pointing to it or naming it. Op1 announced the stimulus to the child by raising the receiver, monitored its head position and observed the responses. Operator 2 presented the stimulus and recorded the responses by means of the touch screen. The child was instructed to look forward to Op1 to see the raising of the receiver. A stimulus was presented only once, unless the child was inattentive, which was judged by Op1. Feedback, in the form of a voice calling "hello" out of the correctly identified loudspeaker, was introduced to minimize picture bias, since a preference for one picture could still exist with the smurfs.

The children were familiarized with the task with three loudspeakers. The number of loudspeakers was gradually increased from three loudspeakers at -60°, 0° and 60°, over five loudspeakers at -60°, -30°, 0°, 30° and 60° to nine loudspeakers at -60°, -45°, -30°, -15°, 0°, 15°, 30°, 45° and 60°. Non-used loudspeakers, telephones and pictures were covered with black

curtains. Each test consisted of three repetitions for each loudspeaker, which resulted in 9, 15 and 27 presentations in the test with three, five and nine loudspeakers, respectively. In total each child listened to 51 stimuli. Adults performed only the nine-loudspeaker task without familiarization and localized 27 stimuli. A localization test with children took on average 13.5 minutes for the three-, five- and nine-loudspeaker tasks together. The nine-loudspeaker task alone lasted for 8 minutes with children and 3 minutes with adults, on average.

Error measures

The RMS error is often used as a measure of localization performance (Litovsky, Parkinson, Arcaroli et al., 2004; Lorenzi, Gatehouse, and Lever, 1999a; van Hoesel and Tyler, 2003). With this measure large errors have a large impact. The MAE is thought to be of greater use with children as short instances of inattentiveness often lead to large errors that are not attributable to localization difficulties. When using the MAE these errors are less emphasized because all errors are weighted equally, independent of their size.

Results

In Figure 3 box plots of the MAE (°) for the different age groups, denoted in years, are displayed. Adults are labeled '18+'. Median MAEs for the 4 year olds, 5 year olds and 6 year olds were 5°, 2° and 1°, respectively. For the RMS errors, the corresponding values were 10°, 6° and 4°. With adults, both the RMS error and MAE had a median value of 0°. A Kruskall-Wallis test revealed significant differences between groups for both the RMS error ($\chi^2 = 17.5$, $p = 0.001$) and the MAE ($\chi^2 = 16.6$, $p = 0.001$). Additional analyses indicated that this effect could be attributed to the worse data of the 4 year olds. When the adult data were excluded, the age effect

was still significant (RMS error: $\chi^2 = 13.0$, $p = 0.002$; MAE: $\chi^2 = 12.0$, $p = 0.003$). Localization data of 5 year olds, 6 year olds and adults mutually did not differ significantly (RMS error: $\chi^2 = 5.427$, $p = 0.66$; MAE: $\chi^2 = 5.427$, $p = 0.66$). The variation clearly was largest in the youngest group. In Figure 4 results are shown for individual 4-year-old children, arranged according to age.

Experiment 2: Sound Lateralization – ITD JND

The processing of ITD cues was investigated in a lateralization task with headphones. An adaptive procedure, estimating the just noticeable ITD, or ITD JND, was modified to the interest and attention span of young children.

Materials and Methods

Subjects

Forty-nine normal-hearing children between 4 and 9 years of age (25 boys and 24 girls; 4y (13), 5y (12), 6y (5), 8y (5), 9y (14)) were tested on sound lateralization skills. In addition, 16 adults between 19 and 24 years of age (mean age of 22 years) participated in the experiment as a control group.

Setup

The test setup consisted of a Dell Latitude D610 laptop connected to an external Hammerfall DSP Multiface soundcard and Sennheiser HD250 Linear II headphones. The stimulus level was controlled by the Hammerfall DSP Mixer, with minimum slider steps of 0.1

dB. Data were collected with the APEX (Application for Psycho-Electrical eXperiments) software interface (Laneau, Boets, Moonen et al., 2005). APEX allows the automatic administration of different sorts of tasks with one interface.

Stimuli

Stimuli were generated in Matlab 6.5 and checked on the scope (Le Croy 9304AM) prior to testing. A click train with a rate of 160 clicks per second was band-pass filtered retaining only harmonics 2 to 5. This signal was chosen in the light of future testing of bilaterally cochlear-implanted children with the same stimuli. With a rate of 160 Hz two harmonics of the signal fall in each channel of the 22-channel filter bank of the Cochlear implant, such that F0 beats are present. A lower rate is not advisable, as it is known that ITD sensitivity and binaural unmasking effects become smaller at the lowest frequencies (Klumpp and Eady, 1956).

Each stimulus consisted of a 1-sec reference signal without ITD (diotic signal), a 1-sec pause and a 1-sec target signal with a certain ITD. ITDs were introduced by shifting one channel in time relative to the other channel. They ranged from 0 µsec to 2000 µsec, to the left, indicated by a '-', or to the right, indicated by a '+'. Between 0 µsec and 1500 µsec a stimulus was made for each 10-µsec step, between 1500 µsec and 2000 µsec for each 100-µsec step only. A linear ramp was applied to all signals, with a rise and fall time of 50 msec. Figure 5 displays the time structure of the filtered click train stimulus. The reference channel is shown in panel a, while panel b shows a 700-µsec-delayed channel. Other panels depict stimuli used in the BMLD experiment.

Test Protocol

Stimulus level adjustment

To adjust the stimulus level the sliders of the soundcard mixer were moved until the filtered click train had a comfortable level. The average presentation level at each individual ear was 67.9 dB SPL for adults and 71.2 dB SPL for children, with respective standard deviations of 0.9 dB and 1.5 dB. Subsequently, subjects were asked to point to the perceived position of the reference stimulus on their head to assure that loudness was balanced at both ears. If the perception was not centered, the level was changed at one side until the sound was perceived at the center. With children, it was only checked whether they heard the signal in the middle. Unless the child indicated it otherwise, the level was always set identically at both ears. It is assumed that loudness is more or less balanced in normal-hearing people. Furthermore, a small deviation of the perception from the center may not necessarily be a problem, as the target signal is judged relative to the reference signal. In adults the level difference between the left and the right ear was never larger than 2.7 dB, and most of the subjects needed no or only a very small adjustment.

Lateralization test

Subjects were told that they would hear a reference signal in the middle of their head, followed by a signal to the left or to the right. Their task was to indicate whether the second sound was to the left or to the right compared to the first signal. Adults responded by clicking on the corresponding button on a computer screen. In children lateralization responses were obtained by means of a game. Three pictures of a train, one from the left side, one from the right side and one from the front (Figure 2, panel b), represented a signal perceived at the left ear, a signal perceived at the right ear and the reference signal, respectively. The pictures were placed in front of the child, spaced far enough to indicate the directions. The task was introduced by a little

story: *"This train is coming from the front. A second train is coming either from there (left) or there (right). The driver of the first train cannot see which train is arriving. Only you can hear which train it is, so you have to help the first train. First you always hear this train (front), but then you should listen very carefully whether the second one comes from there (left) or there (right)."* The child responded by indicating the appropriate picture. The test operator was seated in front of the child and entered the response in the computer. No feedback was given, as well with adults as with children.

The ITD was varied adaptively with a two-down one-up rule, which estimates the 70.7%-point on the psychometric function (Levitt, 1971). The test started with a target stimulus with a large ITD, namely + or - 700 µsec. The ITD was decreased after two correct answers and increased after one incorrect answer. In adults the initial step size of 100 µsec was changed to 40 µsec after one reversal and to 10 µsec after three reversals. With children the step size was made smaller only after three and five reversals because short instances of inattention occur more frequently and the step size might become too small at the beginning of the test. A test ended after six reversals and the minimal audible ITD or ITD JND was calculated as the mean absolute ITD of the last four reversals. The mean duration for the measurement of one ITD JND was 3.5 minutes for the children and 2.5 minutes for the adults.

If subject's attention allowed, three JND estimates were obtained. In some cases an additional fourth test was administered: in adults if results varied with more than 30 µsec – which was the case for only one subject – and in children if the smallest JND deviated with more than 80 µsec from the second smallest or if all three JNDs were higher than 40 µsec.

Training

To familiarize the children with the lateralization task, a training phase preceded the actual experiment. First a sound with an ITD of -700 μsec (perceived at the left), a sound with an ITD of +700 μsec (perceived at the right), and the reference signal without ITD were presented separately a few times, until the child was able to indicate the appropriate picture. If a child was unable to point to a side after several attempts, the test was stopped. This was the case for 2 children. For the remaining children a more extensive training trial followed, with the stimuli of the actual test – target signal preceded by reference signal – but the ITD fixed at +/- 700 μsec. After five consecutive correct responses the experimenter proceeded with the actual test. If children seemed to understand the task but nevertheless were not able to give five consecutive correct responses the training trial was interrupted prematurely but the actual test was still administered. Nevertheless, data of children who did not perform significantly above chance level (69% or higher) in the training trial were excluded from the analysis. This concerned 4 children.

Results

Figure 6 shows the median of the 'ITD2best' and the 'ITDbest' for the different age groups, denoted in years, with the 'ITD2best' as the average of the 2 best results for each subject and the 'ITDbest' as the best result of each subject, both in μsec. The group of adults is labeled '18+'. Data of children who did not perform significantly above chance level (69% or higher) in the training trial were excluded. Six 4-year-old children were omitted. Two of them, AD (4;1y.) and KB (4;3y.), were not able to give responses at all. Four others, KD (4;0y.), AM (4;7y.), JD (4;9y.) and ES (4;11y.), seemed to be guessing. All older children accomplished the training

successfully. The median 'ITD2best' for seven 4 year olds was 34 μsec. The 5, 6, 8, 9 year olds and adults had a median 'ITD2best' of 15 μsec, 31 μsec, 24 μsec, 16 μsec and 10 μsec, respectively.

A Kruskall-Wallis test, including 'ITD2best' data from 43 children and 16 adults, revealed a significant age effect ($\chi^2 = 27.1$, $p <= 0.001$). To find out whether this significance was due to the difference between 4 year olds and the others, or between adults and the others, or both, separate analyses were done with either the adults or the 4 year olds omitted. A Kruskall-Wallis test on the results of the 5, 6, 8, 9 year olds and adults still showed a significant effect of age ($\chi^2 = 21.3$, $p < 0.001$), while results of the 4, 5, 6, 8 and 9 year olds mutually did not differ significantly ($\chi^2 = 7.2$, $p = 0.125$).

Because of the large variation in the youngest group, individual results from all thirteen 4-year-old children are shown in Figure 7, plotted according to age in years and months. Their 'ITDbest' as well as there 'ITD2best' is displayed, in μsec. Black bars represent missing values due to children not able to do the task at all or due to lack of attention after one run. For the sake of completion, the results of the children performing below significance level on the training trial are also included.

Experiment 3: Binaural Masking Level Differences

Another way of measuring the functionality of interaural time differences consists of measuring the amount of unmasking obtained due to different interaural time differences of signal and noise (binaural masking level difference or BMLD).

In the next experiment a BMLD procedure is described that was modified to the interest of young children.

Materials and Methods

Subjects

BMLDs of 23 normal-hearing children between 4 and 6 years of age (13 boys and 10 girls; 4y (11), 5y (9), 6y (3)) were collected. The results of 5- and 6-year-old children will be taken together because of the small number of 6 year olds (6;0 – 6;2 years). Ten normal-hearing adults, between 19 and 25 years of age (mean age of 22 years), served as a reference group.

Setup

Part of the hardware for this experiment was the same as for the lateralization task: a Dell latitude 610 was connected to an external Hammerfall DSP Multiface soundcard, which delivered the stimulus to Sennheiser HD250 Linear II headphones. The stimulus level was controlled through the Hammerfall DSP Mixer. When testing children a touch screen was connected to the pc. The test operator could monitor the test through a second pair of headphones. The APEX software was used to run the adaptive tests and to enter and record the responses. With children, APEX Child Mode (Boets, Wouters, van Wieringen et al., 2006) was used for making the task interesting to them. In this child mode adult buttons are replaced by pictures, and animations are introduced to retain children's attention.

Stimuli

Stimuli were based on those of the lateralization task. BMLDs for a time-delayed filtered click train were assessed in children as well as in adults. White noise, band-pass filtered between 200 Hz and 1000 Hz and with a duration of 1.32 sec, was used as the masking noise. One stimulus consisted of two 400-msec trains of clicks, separated by a 200-msec pause. For each

signal-to-noise ratio between + 15 dB and – 70 dB, separate stimuli were generated in Matlab 6.5, with a time delay of half a period or 3.125 msec (dichotic) and without a time delay (diotic) between channels. One fixed noise sample was used in all observation intervals of this experiment (frozen noise) and the noise was perfectly correlated at both ears. The time representation of the filtered click train is visible in Figure 5, with the reference channel in panel a, and the 3.125-msec-time-delayed channel in panel c.

Additional stimuli were used with adults. A filtered click train with a phase delay of π was added. The time representation of this signal is depicted in panel d of Figure 5, in comparison with panel a, which shows the reference signal. To compare our BMLD results with other BMLD results in the literature, adults also performed several tests with a 500-Hz sinusoid as the signal. White noise was band-pass filtered to obtain two noise types: a wideband noise with cutoff frequencies of 200 Hz and 1000 Hz and a 1/3-octave narrowband noise with cutoff frequencies of 445 Hz and 561 Hz.

Test Protocol

Masked thresholds were assessed in diotic conditions (N_0S_0), conditions with a time-delayed signal (N_0S_τ) and conditions with a phase-delayed signal (N_0S_π). The BMLD is the difference between the diotic condition and one of the dichotic conditions. With children N_0S_0 and N_0S_τ thresholds were measured for the filtered click train only. Both conditions were measured twice, yielding two BMLD estimates for the time-delayed filtered click train. The four measurements (2 x 2) were divided over two sessions, on two separate days or one in the morning and one in the afternoon. The order of measurements was counterbalanced with respect to diotic or dichotic stimulation. To adults N_0S_0, N_0S_τ and N_0S_π thresholds were administered for the filtered click train, and N_0S_0 and N_0S_π thresholds for the 500-Hz sinusoid in wideband as well as

in narrowband noise. With a test and a retest, adults executed 7 x 2 measurements, resulting in 4 x 2 BMLD estimates: for the time-delayed filtered click train, the phase-delayed filtered click train, the 500-Hz sinusoid in narrowband noise and in wideband noise. The order was randomized in each series of measurements, with a pause between two series.

The calibrated noise level was 75 dB SPL at each ear. This way the noise was comfortably loud while the loudest signal was not uncomfortably loud. To assure this and to familiarize subjects with the stimuli, they heard a sample of the signal and the noise separately, and of the signal in the noise.

Thresholds were determined by means of a two-down one-up adaptive procedure, which led to the 70.7%-point in the psychometric function, in a 3AFC task. Adults were instructed to listen to the three noise intervals and use the mouse to indicate the interval containing the signal on a computer screen. Feedback was given in the form of a green or a red thumb, pointing up or down, respectively. For children the task was embedded in a game. On a touch screen three cars of the APEX Child Mode were shown (Figure 2, panel c), moving simultaneously with the three noise intervals. The task was introduced by a little story: *"Daddy monkey is picking up his son at school. Now three cars arrive, but little monkey does not know which car belongs to his dad. Therefore he has to listen very carefully, because his dad will hoot when he arrives. Can you help little monkey to find his dad? Listen very carefully to the hooter!"* Children touched the car on the screen. To motivate the child, feedback was provided in the form of an ape coming out of the car in case of a correct answer, or the trunk of an elephant in case of an incorrect answer.

The adaptive staircase started at a signal-to-noise ratio of + 15 dB. The signal level changed with steps of 6 dB at the start, 3 dB after three reversals and 1 dB after five reversals. A run stopped after six reversals and threshold was calculated as the mean signal-to-noise ratio at

the last four reversals. The mean duration for one BMLD measurement, including two threshold estimations, was 13 minutes for children and 7 minutes for adults.

With children, a training phase at a fixed signal-to-noise ratio of + 15 dB preceded the actual test. This test was not started before five consecutive correct answers in the training phase.

Results

Median thresholds and BMLDs for the different conditions are listed in Table 1. As only three 6-year-old children were tested (all between 6;0 and 6;2 years of age), 5- and 6-year-old children were analyzed as one group. Figure 8 focuses on the results for the time-delayed filtered click train only, which was used with adults as well as with children. In this figure N_0S_0 thresholds – white bars – and N_0S_τ thresholds – light grey bars – are plotted next to BMLDs – dark grey bars. Median N_0S_0 thresholds were -8.5 dB, -9.4 dB and -12.6 dB for the 4 year olds, 5/6 year olds and adults, respectively. Median N_0S_τ thresholds were -16.5 dB, -17.7 dB and -22.4 dB. For the BMLD, median values for the three groups were 7.5 dB, 9.4 dB and 9.8 dB.

A Kruskall-Wallis test revealed significant differences in N_0S_0 ($\chi^2 = 13.888$, $p = 0.001$) and in N_0S_τ ($\chi^2 = 18.443$, $p < 0.001$), but not in BMLD ($\chi^2 = 2.929$, $p = 0.231$). Mann-Whitney tests were executed to find out which means differed significantly in N_0S_0 and N_0S_τ. These tests showed that the results of the children mutually did not differ significantly (N_0S_0: difference = 0.9 dB, $U = 57.5$ $p = 0.601$; N_0S_τ: difference = 1.2 dB, $U = 40.0$ $p = 0.109$). However, both the thresholds of the 4-year-old children (N_0S_0: difference = 4.1 dB, $U = 5.5$ $p < 0.001$; N_0S_τ: difference = 5.9 dB, $U = 0.0$ $p < 0.001$) and of the 5/6-year-old children (N_0S_0: difference = 3.2 dB, $U = 15.5$ $p = 0.003$; N_0S_τ: difference = 4.7 dB, $U = 11$, $p = 0.001$) were significantly different from the adult thresholds.

With adults, median BMLD values from 9.8 dB (time-delayed filtered click train) to 21.1 dB (500 Hz in narrowband noise) were found. A Wilcoxon signed rank test showed that the 180° phase-shifted filtered click train was statistically significantly better detected than the time-delayed filtered click train (difference = 4.9 dB, Z = -2.499, p = 0.012), and also the difference between the BMLDs was statistically significant (difference = 4 dB, t = -2.395, p = 0.017). Interestingly, BMLDs for the phase-delayed filtered click train and the 500-Hz sinusoid in wideband noise did not differ significantly (difference = 0.4 dB, Z = -0.255, p = 0.799). As is also found in the literature, BMLD values for a 500-Hz sinusoid were larger in narrowband noise than in wideband noise (difference = 7.7 dB, Z = -2.803, p = 0.005). This difference was caused by the fact that the diotic sinusoid was much better detected in the wideband noise (difference = 9.4 dB; Z = -2.803, p = 0.005) while for the detection of the phase-shifted sinusoid a significant but smaller difference was found between wideband and narrowband noise (difference = 3.5 dB; t = -2.701, p = 0.007).

Discussion

Feasibility of test procedures

The results obtained in the three experiments indicate that procedures have been adequately adapted to the interest and attention of young children. They enjoyed the games and liked participating in the task. Children of 5 years of age executed the psychophysical tasks successfully and their attention span was long enough to complete the tests. Pilot tests showed that for children younger than 4 years of age, tasks were too demanding, even with simplified procedures. Between 4 and 5 years of age some children performed as well as 5 year olds, while

others had difficulties understanding the task or maintaining attention throughout the test, resulting in worse scores.

The sound localization and lateralization task each are executable in less than 15 minutes. Total test duration to obtain three ITD JNDs was on average 10.5 minutes. A localization test with increasing number of loudspeakers lasted for 13.5 minutes on average. The BMLD task took somewhat longer, with a mean duration of 26 minutes to obtain two BMLD estimates.

Binaural hearing in adults

The localization setup, modified for testing children, yielded ceiling scores in adults. Previous results of Van den Bogaert et al. (2006) showed that increasing the number of loudspeakers and/or using a stimulus with a smaller bandwidth increases the number and magnitude of the errors.

Lateralizaton and BMLD results agreed quite well with values recorded in the literature. The median ITD JND for the 160-Hz filtered click train, namely 10 µsec, corresponds to the value obtained by Klumpp and Eady (1956) for repeated clicks. The BMLDs of Yost and Dolan (1978) for time- and phase-delayed pulses (around 12 dB), obtained with 2 subjects, were in the same range as our BMLD results for phase- or time-delayed filtered click trains (10 dB – 14 dB). The trend of increasing BMLDs with decreasing bandwidth was also found in the study of Staffel et al. (1990). They recorded BMLD values of 14.4 dB and 18.3 dB for a 500-Hz sinusoid in broadband (800 Hz) and narrowband (100 Hz) noise, respectively, with a 3AFC task. Our data are very similar, with nearly the same value for wideband noise (13.4 dB), and a somewhat higher BMLD in narrowband noise (21.1 dB). The similarity in the BMLDs for the phase-delayed filtered click train and for the 500-Hz sinusoid, both in wideband noise, can be explained

by the similarity in frequency content, since the harmonics of the filtered click train are located around 500 Hz.

Binaural hearing in children

Studies of the anatomy and physiology of the brainstem and cortical pathways, involved in hearing in general or binaural hearing in particular, show that myelinization of axons goes on until puberty (Moore, 2002; Moore and Guan, 2001). This myelinization is important for faster signal transmission and might therefore improve the preservation of timing information in auditory stimuli. It is, however, not clear whether this really has an influence on binaural tasks such as the ones measured in our study. Our results demonstrate that no clear developmental trend is visible in these three tasks of binaural hearing. Children of 4 years of age lateralize sounds as well as 9 year olds and obtain the same amount of binaural unmasking as adults do. It therefore seems that the increasing neural complexity does not give rise to an important increase in ITD-processing complexity.

Only on sound localization 4 year olds perform worse than 5 year olds, while these 5 year olds perform as well as adults. The difference between 4 and 5 year olds can presumably be attributed to differences in their task attitude and cognitive capacities. In a pilot experiment 3-year-old children were not able to discriminate between three loudspeakers at –90°, 0° and +90°, while previous studies have shown that infants of only 1 year of age demonstrated correct head turnings on sounds deviating only 10° from midline (Ashmead, Davis, Whalen et al., 1991). Some 4 year olds who performed well with three loudspeakers were not able to give reasonable responses with nine loudspeakers, sometimes indicating a loudspeaker in the hemifield opposite that of the stimulus. Although efforts have been made to make the task as child friendly as possible, the aspect of identification involves that a certain level of task-focusing is necessary.

Some children localized the telephone signal as well as adults, which shows that mature sound localization is possible at this age.

The lower ITD sensitivity of children compared to adults might also be explained partially by the fact that the task was highly demanding and children sometimes do not get to very low ITD values due to attention factors. The fact that attention or other momentary factors are important agents in the task outcomes is visualized in the rather large variation in the results, inter-individually as well as intra-individually. Another explanation for the child-adult difference is the difference in test setup. As children were not tested in a sound-attenuating booth the background-noise level was higher for them than for the adults. This could make it harder for them to concentrate on the sound stimuli and hear the subtle differences. The fact that 4-year results were not worse than the 5-year results is probably attributable to the omission of the data of children performing below chance level.

In the BMLD paradigm, effects of cognitive capacities and attention are reduced considerably. Two conditions, for which other than binaural variables are more or less the same, are compared in each child. Children do have higher detection thresholds in noise (Schneider, Trehub, Morrongiello et al., 1986; Schneider, Trehub, Morrongiello et al., 1989), as is confirmed in the present study by the significantly higher N_0S_0 and N_0S_τ thresholds for children compared to adults. The higher thresholds might be due to nonlinear changes in the neural representation of signal and noise during development (Schneider, Trehub, Morrongiello et al., 1989), but also to different response criteria or to a lower attention level. These effects are more or less ruled out when comparing the N_0S_0 and N_0S_τ condition. Moreover, thanks to the testing in noise, background noise level is a less disturbing factor in the BMLD test. The equivalent values in adults and children constitute a very important result. Still, children can perform worse in one condition because of an instance of inattention, and therefore several measurements have to be

executed on different days and the order of conditions has to be switched. As indicated by the relatively large variance in the 4-year results, more than two measurements are recommended to obtain an accurate estimate.

It is important to stress that we only measured some aspects of binaural hearing. It is possible that other aspects do manifest a developmental effect. Some evidence of an increase in binaural advantages in speech understanding in noise with age exists. Summerfield et al. (Reference Note 1) found an improvement in binaural speech understanding in noise up to the age of 14. They measured Binaural Speech Intelligibility Level differences (BILD), the speech equivalent of the BMLD. The BILD refers to the improvement in speech intelligibility due to relative interaural differences of a speech and a noise signal. In the study of Cameron et al. (Reference Note 2), who also measured speech understanding in different noise conditions, children of 5 years of age had a significantly smaller spatial advantage than children of 7 to 11 years of age. The spatial advantage obtained by 6-year-old children was significantly smaller than that of the 8 and 11 year olds.

Cochlear-implanted children

The issue of a development in binaural hearing is important in the framework of bilateral cochlear implantation. Recently a lot of research has been done on the benefit of bilateral versus unilateral cochlear implants. In adults head-shadow and summation effects have been shown (Muller, Schon, and Helms, 2002; Schleich, Nopp, and D'Haese, 2004; Senn, Kompis, Vischer et al., 2005; van Hoesel and Tyler, 2003), but only very limited evidence of small binaural-squelch effects could be established (Muller, Schon, and Helms, 2002; Schleich, Nopp, and D'Haese, 2004; van Hoesel, 2004). One possible reason for this is that the mechanics of current cochlear implant processors do not allow providing listeners with detailed binaural cues. Another

possibility is that adults, who never learned to make use of binaural cues because they were deaf for a long time, or who were quasi-normal hearing before, might not be able to learn to process binaural cues through cochlear implants at a later age. If binaural hearing capacities are not complete at birth, but take some years to mature, it might be beneficial to bilaterally implant deaf children early in life, before the maturation process ends.

In Belgium 45 children between 2;6 and 12 years of age have been bilaterally implanted. The procedures described in this article will be used to measure the binaural capacities of these children.

Conclusions

The modified test procedures for sound localization, lateralization and binaural masking level differences are feasible with children from the age of 4. Furthermore, results show that at least some binaural hearing capacities are fairly well acquired at this young age. The results of 4 year olds did not differ significantly from the results of 9 year olds on the lateralization task. On the BMLD test 4 year olds even performed at adult level. Observed differences between 4 year olds and older children, in the localization task, or between children and adults, in the lateralization task, are probably primarily attributable to factors other than hearing skills, like task comprehension, attention and testing conditions. Future research has to reveal whether a development exists in other binaural hearing tasks that tap more central processes, like spatial speech understanding in noise.

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List of Figures

Figure 1: Localization test setup for children. A touch screen, connected to the computer in the control room, allows managing the test from the test room.

Figure 2: Pictures used in the three experiments: a smurf of the localization setup (a), the trains of the lateralization setup (b) and the Apex Child Mode screen with cars (c).

Figure 3: Box plots of the mean absolute error, in degrees, for each age group, denoted in years. The adult group is labeled '18+'.

Figure 4: Mean absolute errors, in degrees, for individual 4-year-old children, arranged according to age, denoted in years;months (y;m).

Figure 5: Time structure of a 60-msec sample of the filtered click train. Panel a shows the reference signal, presented to the right ear. Panel b, c and d present the signal at the left ear of different experiments. In panel b a 700-μsec-delayed signal, which was used in the lateralization experiment, is displayed. Panel c and d show the signals that were used in the BMLD task, with a 3.125-msec delay and a π delay or phase reversal, respectively.

Figure 6: Box plots of the just noticeable differences (JND) in interaural time differences (ITD), in μsec, for each age group, denoted in years, with either the two best results of each subject ('ITD2best', grey bars) or the best result of each subject ('ITDbest', white bars) considered. The adult group is labeled '18+'.

Figure 7: Just noticeable differences (JND) in interaural time differences (ITD), in μsec, for the individual 4 year olds. The average of the two best results of each subject ('ITD2best', grey bars) as well as the best result of each subject ('ITDbest', white bars) is shown. Results are arranged according to age, denoted in years;months (y;m). Black bars indicate missing values, due to children not able to accomplish the task.

Figure 8: Box plots of detection thresholds of the filtered click train in the diotic condition ('N0S0', white bars) and in the dichotic condition, with a time delay in the signal ('N0Sτ', light grey bars), and of the difference between these thresholds, the binaural masking level difference ('BMLD', dark grey bars), all in dB. Results are displayed separately for the 4 year olds, 5/6 year olds, and adults, labeled '18+'.

Figure 1 Van Deun et al

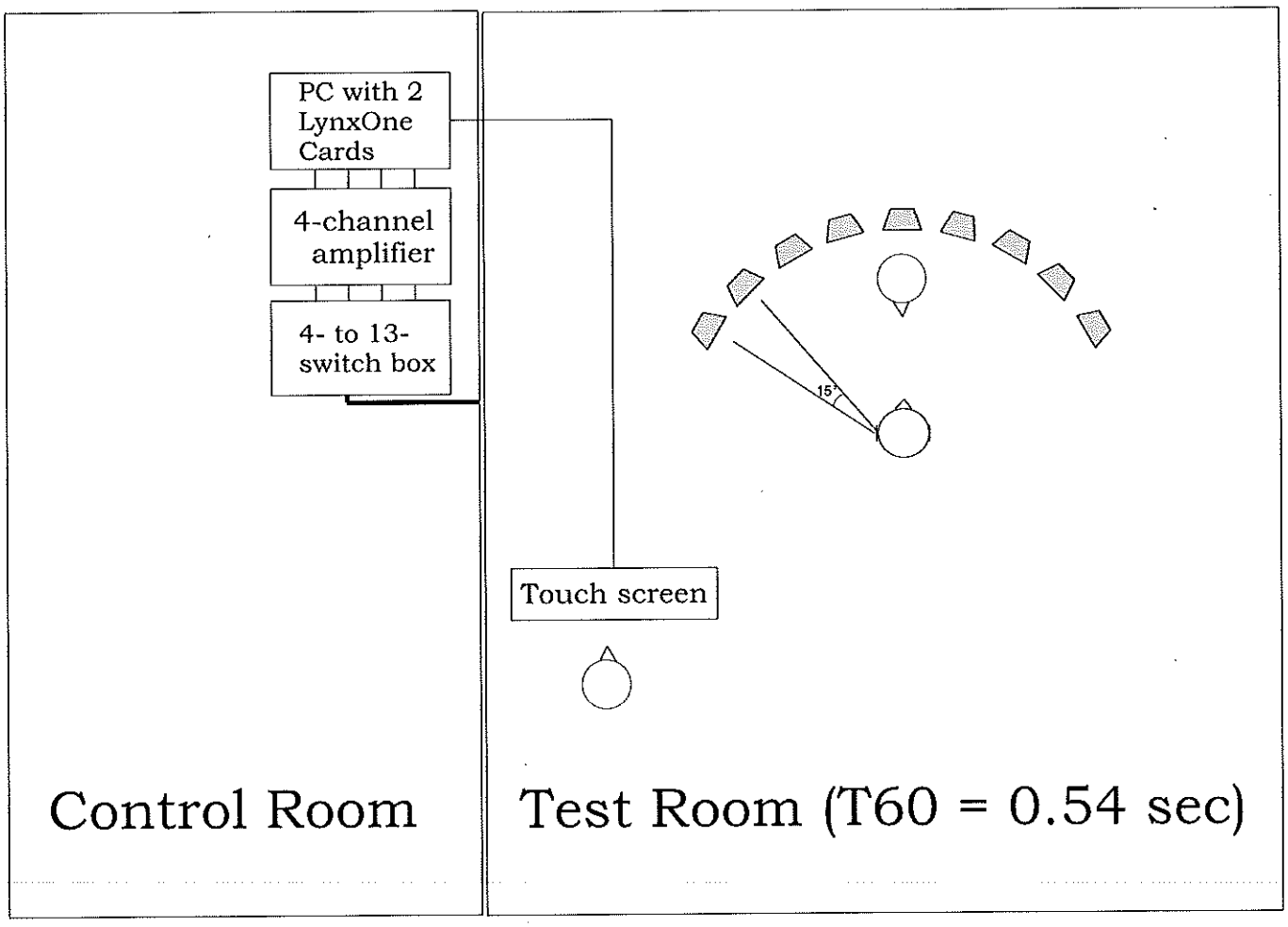
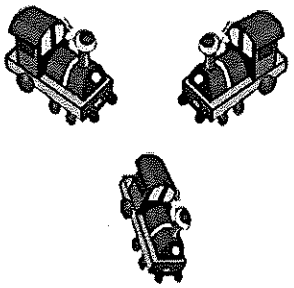


Figure 2 Van Deun et al

a)



b)



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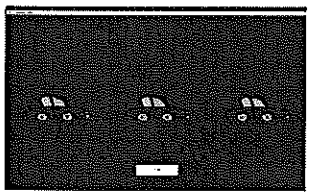

Figure 3 Van Deun et al

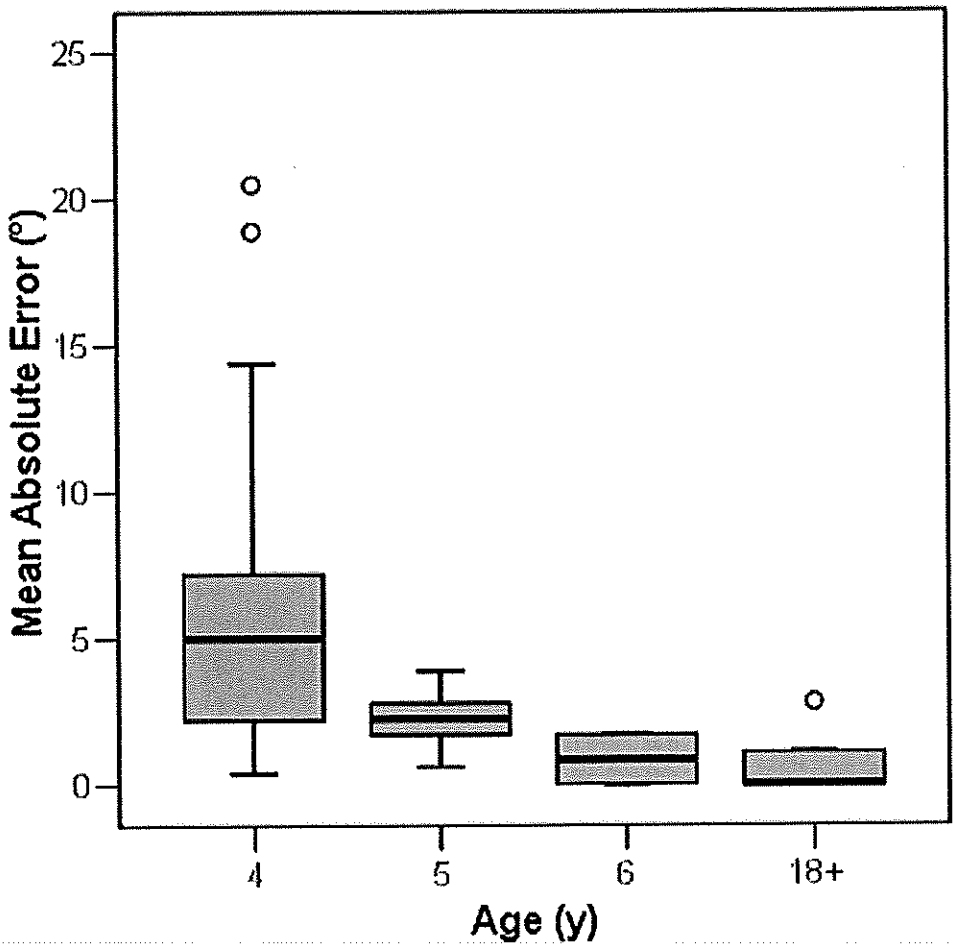

Figure 4 Van Deun et al

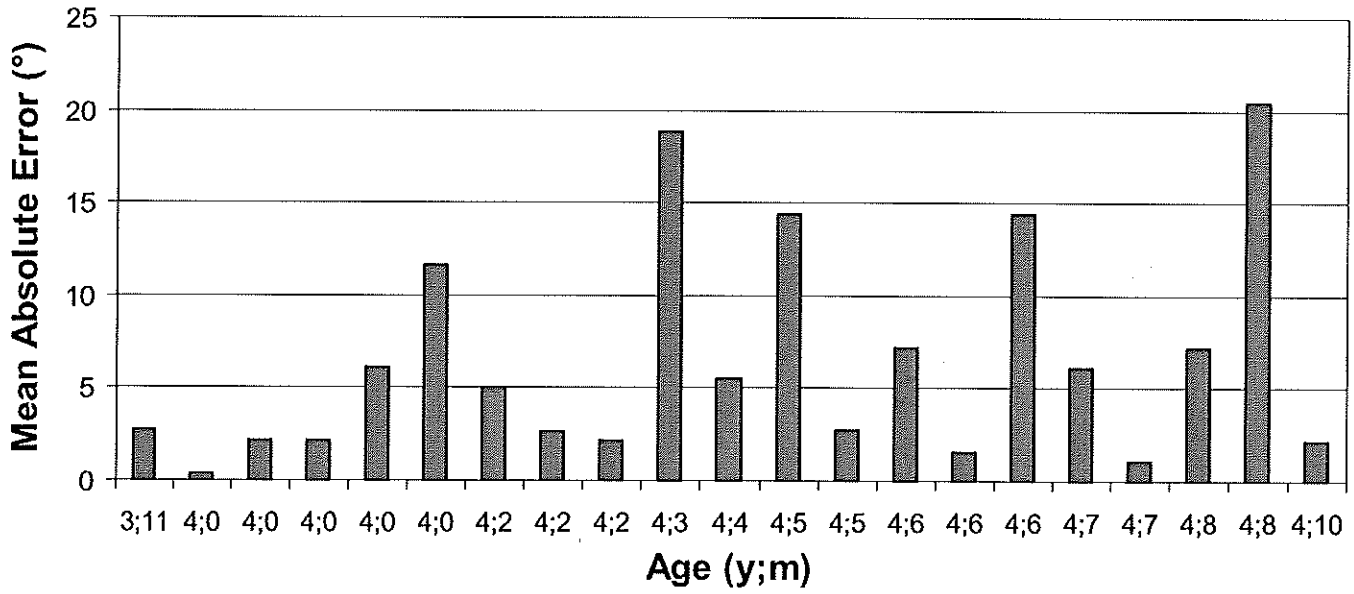

Figure 5 Van Deun et al

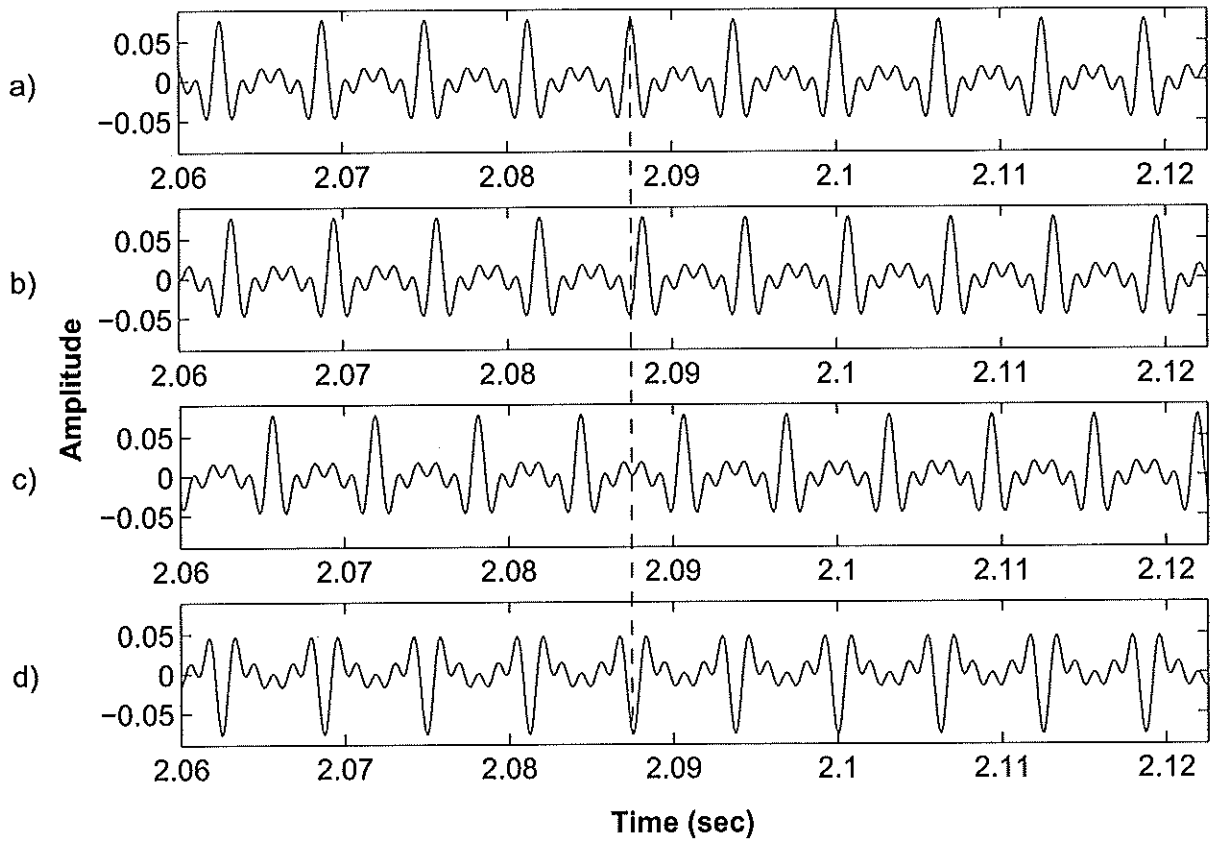

Figure 6 Van Deun et al

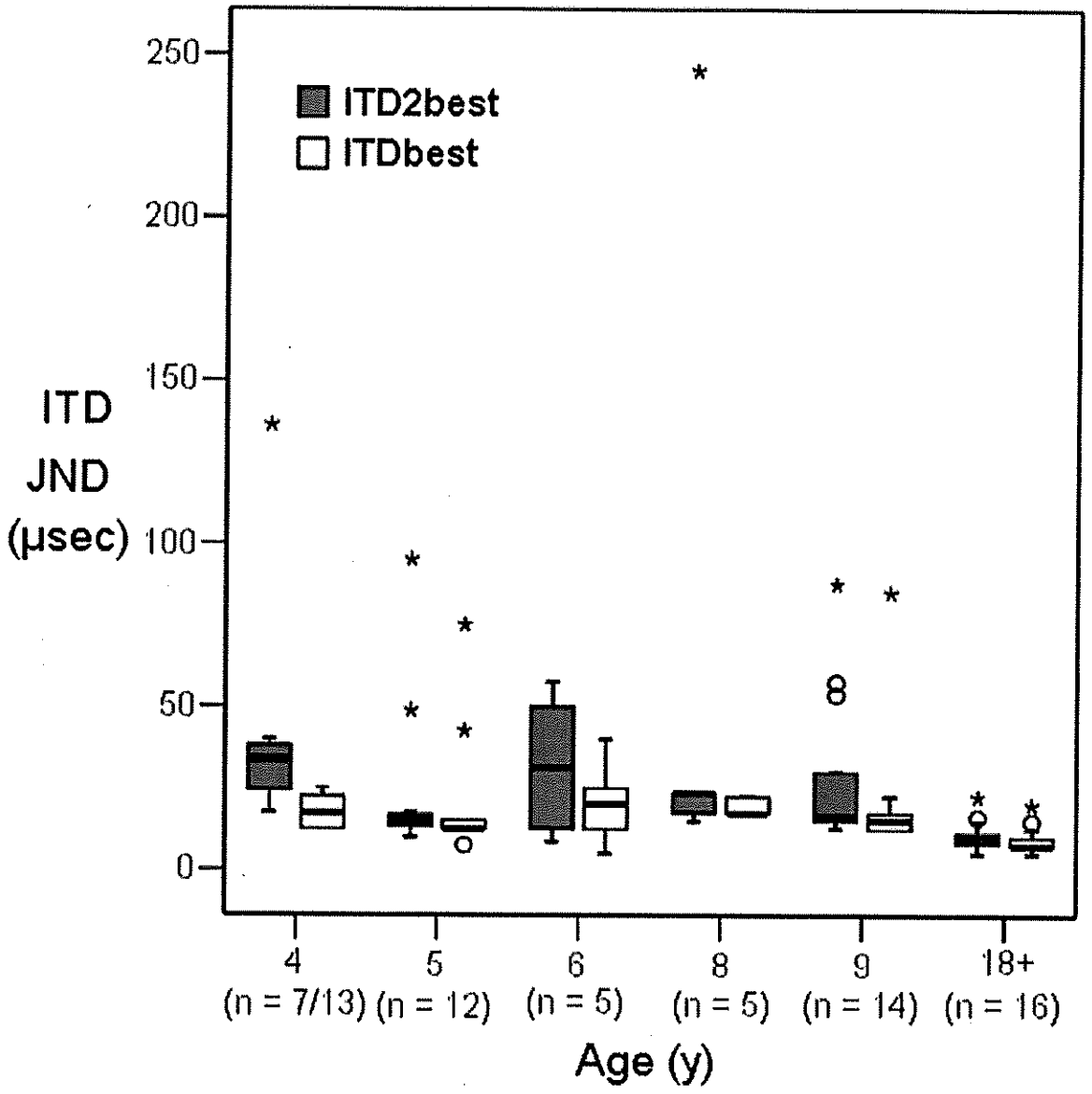

Figure 7 Van Deun et al

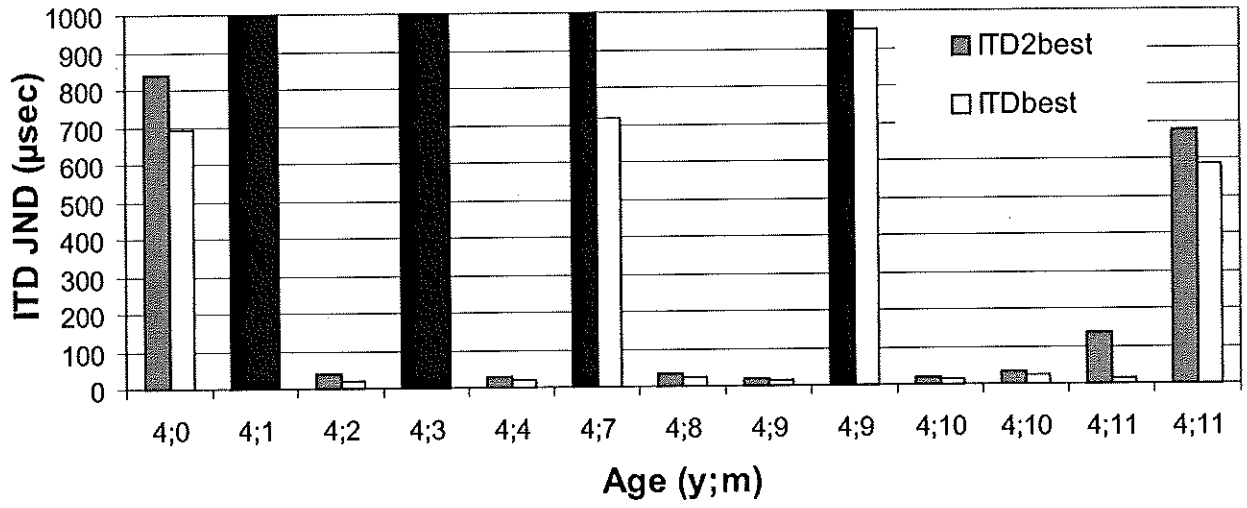

Figure 8 Van Deun et al

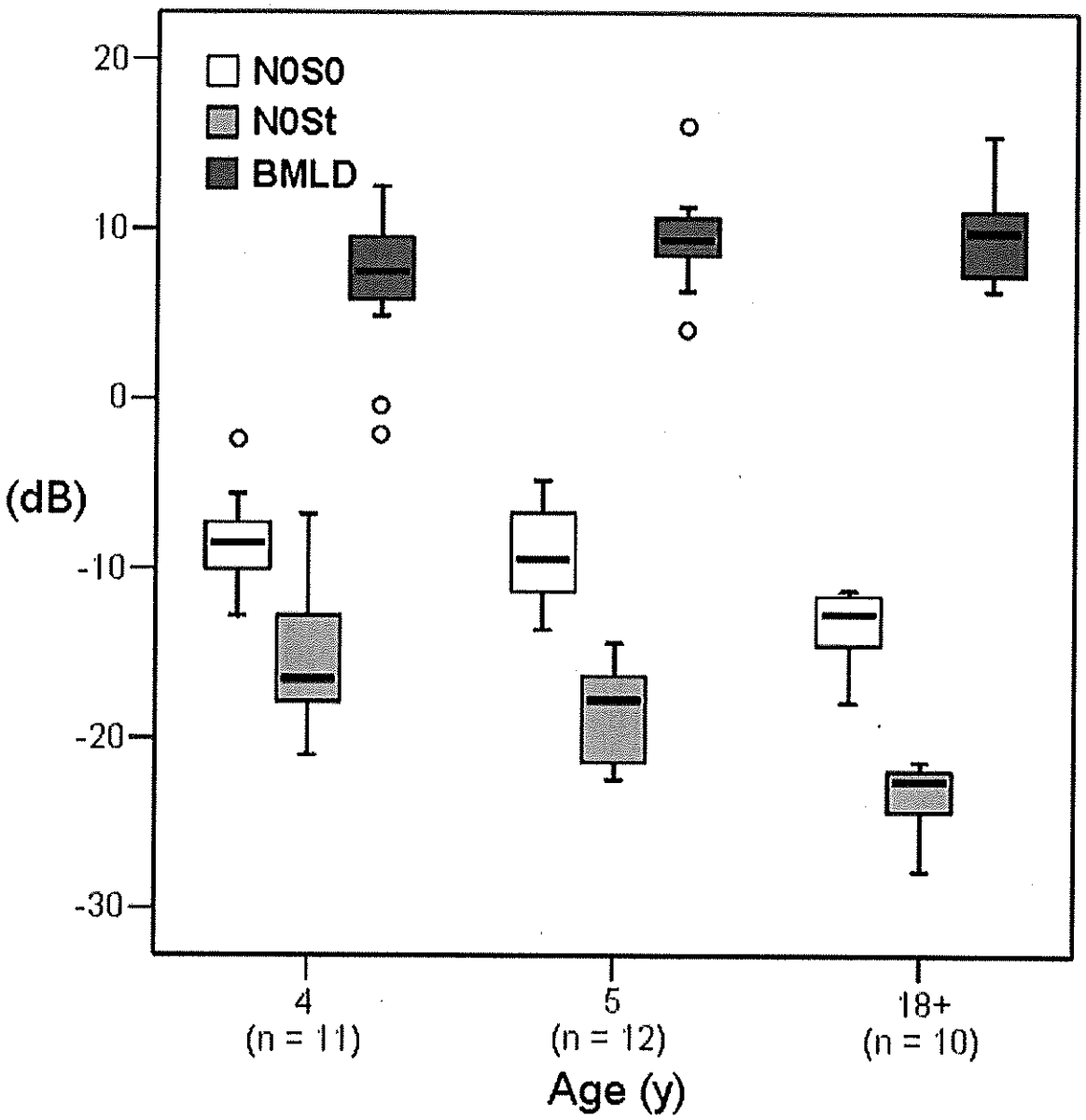

Table 1 Van Deun et al

Table 1: Median thresholds (N_xS_x) and binaural masking level differences (BMLD) of children and adults for the 160-Hz filtered click train and for the 500-Hz sinusoid. The interquartile ranges are given between brackets. A time delay is indicated by a τ, a phase delay by a π. For the 500-Hz sinusoid, thresholds have been determined in wideband as well as in narrowband noise.

			4y (n = 11) [dB]	5-6y (n = 12) [dB]	Adults (n = 10) [dB]
Filtered click train	Wideband noise	N_0S_0	-8.5 (-10.8 – -7.1)	-9.4 (-11.9 – -6.6)	-12.6 (-14.5 – -11.6)
		N_0S_τ	-16.5 (-18.9 – -10.6)	-17.7 (-21.7 – -16.3)	-22.4 (-24.4 – -21.8)
		$BMLD_\tau$	**7.5** (4.9 – 10.3)	**9.4** (8.4 – 10.8)	**9.8** (7.2 – 11.6)
		N_0S_π			-27.3 (-28.1 – -24.9)
		$BMLD_\pi$			**13.8** (11.5 – 15.2)
500-Hz sinusoid	Wideband noise	N_0S_0			-15.6 (-17.6 – -13.8)
		N_0S_π			-29.3 (-30.0 – -28.3)
		BMLD			**13.4** (11.7 – 15.4)
	Narrowband noise	N_0S_0			-4.2 (-6 – -3.5)
		N_0S_π			-25.8 (-27.7 – -23.4)
		BMLD			**21.1** (17.3 – 23.2)