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Masked Speech Recognition by Normal-Hearing 6–13-Year-Olds in Conditions With and Without Interaural Difference Cues

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Abstract

Using the Danish 'børneDAT' corpus, the current study aimed to (1) collect normative masked speech recognition data for 6–13-year-olds in conditions with and without interaural difference cues, (2) evaluate the test–retest reliability of these measurements, and (3) compare two widely used measures of binaural/spatial benefit in terms of the obtained scores. Seventy-four children and 17 young adults with normal hearing participated. Using headphone presentation, speech recognition thresholds (SRTs) were measured twice at two separate visits in four conditions. In the first two conditions, børneDAT sentences were presented in diotic stationary speech-shaped noise, with the sentences either interaurally in-phase ('N0S0') or interaurally out-of-phase ('N0S180'). In the other two conditions, børneDAT sentences were simulated to come from 0° azimuth and two running speech maskers from either 0° azimuth ('co-located') or ±90° azimuth ('spatially separated'). In relative terms, the children achieved lower SRTs in stationary noise than in competing speech, whereas the adults showed the opposite pattern. 12–13-year-old children achieved adult-like performance in all but the co-located condition. Younger children showed generally immature speech recognition abilities. Test–retest reliability was highest for the SRTs in stationary noise and lowest for the spatial benefit scores. Mean benefit was comparable for the two measures and participant groups, and the two sets of scores were not correlated with each other. Developmental effects were most pronounced in the conditions with interaural difference cues. In conclusion, reference data for the børneDAT corpus obtained under different acoustic conditions are available that can guide future research and potential clinical applications.

Keywords

speech test, pediatrics, auditory development, binaural hearing

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Introduction

Children are often in noisy environments such as schools (e.g., Schafer, 2010). Noise in classrooms can lead to poorer learning outcome and thus academic underachievement as it interferes with speech recognition, especially in children with hearing deficits (e.g., Picard & Bradley, 2001; Shield & Dockrell, 2003). As a consequence, reliable methods for diagnosing problems with hearing in noise are important, so that appropriate treatment strategies can be found and good learning outcome be ensured (e.g., Evans & Lepore, 1993).

In clinical practice, speech audiometry is widely used for assessing a listener's hearing abilities (e.g., Lawson & Peterson, 2011). Speech audiometry can be carried out with different speech materials (e.g., phonemes, words, or sentences) and masker signals (e.g., stationary noise, babble noise, or competing speech). Stationary speech-shaped noise is often used as the masker signal because this leads to highly repeatable measurements. Competing speech can increase the ecological validity of a test, but it also introduces acoustic and semantic variability into the measurements. By presenting the speech and masker signals with different binaural cues or from different spatial directions, the ability

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to exploit interaural difference cues for segregating competing signals can be assessed. When intact, this ability can clearly improve speech understanding in noise (e.g., Stecker & Gallun, 2012). When immature or impaired, speech understanding deficits can be expected to occur that require effective diagnosis and treatment strategies (e.g., Gallun, 2021; Litovsky, 2012).

For pediatric applications, different speech tests are available. In Germany, for example, the 'Oldenburger Kinder Satztest' (OlKiSa) was developed for measurements in quiet or speech-shaped noise (Wagener et al., 2006). The OlKiSa consists of three-word pseudo-sentences that include a numeral, an adjective, and a noun (e.g., "Four red flowers"). Neumann et al. (2012) evaluated the OlKiSa in quiet and found it to be usable with children aged 4 years and above. Another example is 'FreeHear', which is available in British English (Moore et al., 2019). As stimuli, digit triplets in babble noise are used. This test has also been found to be suited for children aged 4 years and above. A third example is the 'Hearing In Noise Test for Children' (HINT-C) that was first developed in American English (for an overview, see Schafer, 2010). It is based on 'child-friendly' test lists from the Hearing in Noise Test (HINT) and is carried out in stationary speech-shaped noise. Recently, a Swedish version was developed (Hjertman et al., 2021). For speech and noise presented from a frontal loudspeaker, 6–11-year-old children obtained a mean speech recognition threshold (SRT) of −2.6 dB signal-to-noise ratio (SNR) and adult-like performance at 10.5 years of age.

The 'Listening in Spatialized Noise-Sentences Test' (LISN-S) makes use of virtual acoustics to present speech and masker signals from different directions under headphones (Cameron & Dillon, 2007). Relatively simple, meaningful sentences are used as target speech (e.g., "The boys are watching the game") and two running speech signals (i.e., stories) as maskers. SRTs can be measured in several conditions, for example with the target speech and speech maskers all presented from 0° azimuth ('co-located') or with the target speech presented from 0° azimuth and the two speech maskers presented from ±90° azimuth ('spatially separated'). In this manner, benefit from spatial separation of the competing speech signals can be determined. In their study, Cameron and Dillon (2007) gathered normative data from 82 children aged 5–11 years. On average, the children achieved SRTs of −4.1 and −13.4 dB SNR in the co-located and spatially separated conditions with three different female voices, and thus ∼9 dB of spatial benefit. Moreover, there was a clear trend of decreasing SRTs and increasing spatial benefit with higher age that was driven by the 5-year-olds, suggesting strong binaural developmental effects around this age.

The influence of binaural hearing on masked speech recognition in school-age children was also studied by Koopmans et al. (2018). These authors used a headphone-based digits-in-noise test for their study. In one condition, digit triplets and stationary speech-shaped noise were presented diotically, that is, both signals were interaurally in-phase ('N0S0'). In another condition, the digits were interaurally out-of-phase while the noise was interaurally in-phase ('N0S180'). By calculating the SRT difference for these two conditions, binaural benefit was determined. The participants were 112 children aged 4–12 years and 33 adults aged 18–30 years with normal hearing. Mean SRTs were approx. −9 and −10 dB SNR in the N0S0 condition and −13 and −15 dB SNR in the N0S180 condition (children and adults, respectively), and mean binaural benefit was ∼4 and ∼5 dB. Performance improved with higher age, especially in the N0S180 condition. Binaural benefit increased accordingly.

In a similar study, Wolmarans et al. (2021) used a digits-in-noise test implemented on a smartphone to test ∼600 school-going children aged 6–14 years with average hearing thresholds of ≤20 dB HL (calculated across 1, 2, and 4 kHz and left and right ears). Overall, the children obtained SRTs of −9.2 and −16.4 dB SNR in the N0S0 and N0S180 conditions and thus a binaural benefit of ∼7 dB. Consistent with the results of Koopmans et al. (2018), higher age was associated with lower SRTs, especially in the N0S180 condition, and larger binaural benefit up to 10–12 years of age.

Recently, a Danish sentence corpus for pediatric speech audiometry applications was developed (Koiek et al., 2020). Called 'børneDAT', this corpus is based on the validated sentence materials from the Danish DAT corpus (Nielsen et al., 2014). The DAT sentences all have a simple, fixed structure. That is, they start with a female name ("Dagmar", "Asta", or "Tine") and contain two short, unique, and unrelated keywords. Two examples are "Dagmar tænkte på en teske og en næse i går" ("Dagmar thought about a teaspoon and a nose yesterday") and "Tine tænkte på en dans og en lastbil i går" ("Tine thought about a dance and a truck yesterday"). On a given trial, the participant's task is to repeat the two keywords of the corresponding sentence. For the børneDAT corpus, 11 test lists comprising 20 sentences each that all start with either Dagmar, Asta, or Tine were carefully constructed and evaluated by measuring SRTs in stationary speech-shaped noise under diotic (N0S0) conditions. Twenty normal-hearing children aged 6–12 years were tested. Six test lists were found to be perceptually equivalent. These lists gave rise to a grand average SRT of −2.6 dB SNR and a within-subject standard deviation (SD) of 1.1 dB SNR. The remaining lists were characterized by slightly higher SRTs and slightly lower test–retest reliability but were otherwise equally usable.

The current study aimed to extend the usability of the børneDAT corpus by collecting normative masked speech recognition data for children aged 6–13 years and adults aged 22–28 years in four acoustic conditions. The conditions differed in terms of the type of masker (stationary speech-shaped noise or running speech) and the way the stimuli were presented to the participants' ears (with or without interaural differences between the target and masker signals). Another aim was to evaluate the test–retest reliability of the different measurements. For that reason, SRTs were measured twice at two separate visits for all groups and conditions. A third aim was to compare two widely used measures of benefit from the availability of interaural difference cues in terms of their scores, that is, binaural benefit as studied by Koopmans et al. (2018) and Wolmarans et al. (2021) and spatial benefit as studied by Cameron and Dillon (2007) (see above). The comparison focused on age effects and on the correlation between these scores. In that way, the utility of the two measures for assessing binaural processing abilities in school-age children was addressed.

Methods and Materials

The current study was evaluated by The Regional Committee on Health Research Ethics for Southern Denmark, and ethical approval was not required (case no. 20202000-93). To compensate them for their efforts, all participants received a gift voucher corresponding to 120 Danish crowns per visit.

Participants

Seventy-four children (42 female) between 6 and 13 years of age (mean: 8.9 years) and 17 adults (nine female) between 22 and 28 years of age (mean: 24.7 years) participated. The children were recruited from local elementary schools and the adults via announcements in the local media. To be included in the current study, all participants had to have (1) normal otoscopy results, (2) normal middle-ear function as indexed by type-A tympanograms (compliance of 0.3–1.5 mmho and middle-ear pressure of −100 to +50 daPa), (3) pure-tone hearing thresholds ≤20 dB HL at all standard audiometric frequencies from 250 to 8000 Hz, (4) Danish as their native language, (5) normal language development, and (6) normal cognitive function. The first two inclusion criteria were confirmed using tympanometry and pure-tone audiometry. The other inclusion criteria were verified using a custom-made questionnaire. This revealed that none of the participants had experienced any issues with language or cognitive development. Furthermore, it revealed that all participants came from families with middle to high incomes.

Physical Test Setup

All measurements were performed in a large sound booth in the audiological laboratory at the University of Southern Denmark. An Interacoustics Affinity 2.0 system with RadioEar DD45 headphones was used for the pure-tone audiometry. An Interacoustics Titan system was used for the tympanometry. The speech recognition measurements were controlled via custom-made Matlab software. The stimuli were presented via an RME Fireface UC USB2.0 sound card and supra-aural free-field-equalized headphones (Sennheiser HDA200). The setup was calibrated using a 0.1-dB FUSION sound level meter and a GRAS 43AA-S2 CCP ear simulator kit.

Stimulus Materials

As target speech, the test lists from the børneDAT corpus were used. More specifically, the six lists that previously had been found to be perceptually equivalent (see Introduction) were used for testing, while the other lists were used for training purposes. As masker signals, either stationary noise with the same long-term average speech spectrum as the target sentences or running speech was applied. The running speech consisted of two stories uttered by two female Danish speakers that were taken from the DANTALE-I corpus (Elberling et al., 1989) and the Archimedes project (Hansen & Munch, 1991). All test signals had a sample rate of 48 kHz.

Speech Recognition Measurements

Speech recognition was assessed by measuring 50%-correct SRTs. The masker signals were presented at a fixed level of 65 dB SPL. The target speech level was varied according to the adaptive procedure of the Danish HINT (Nielsen & Dau, 2011), with the initial presentation level being determined based on pilot testing. Four acoustic conditions were tested. In the first two conditions, diotic stationary speech-shaped noise was used. The target speech was either interaurally in-phase (N0S0) or interaurally out-of-phase (N0S180). In the N0S0 condition, the target speech was initially presented at 69 dB SPL, while in the N0S180 condition it was initially presented at 67 dB SPL. In the other two conditions, two running speech maskers were used. The two speech maskers came either from in front (0° azimuth) or from the sides (±90° azimuth) of the listener. The target speech was always presented from in front of the listener. That way, the three speech signals were either co-located or spatially separated. The spatial directions were simulated by convolving the speech recordings with generic anechoic head-related impulse responses measured on an acoustic mannikin (i.e., a KEMAR dummy-head; Gardner & Martin, 1994). In the co-located condition, the presentation level of the target speech was initially set to 73 dB SPL, while in the spatially separated condition it was initially set to 67 dB SPL. The masker signals started 1 second before and ended 0.6 seconds after the target sentences. Responses were scored as correct if both keywords of a given sentence were repeated correctly. On the first four trials, the target level was adjusted in 4-dB steps. Afterwards, a step size of 2 dB was used. Following the presentation of 20 sentences, the SRT was calculated by averaging the SNRs from the fifth to the (hypothetical) 21st trial.

Binaural and Spatial Benefit

In addition to speech recognition in the four acoustic conditions, benefit from the availability of interaural difference cues was examined. To that end, the SRTs for the N0S180 condition were subtracted from the SRTs for the N0S0 condition, yielding binaural benefit scores. Likewise, the SRTs for the spatially separated condition were subtracted from the SRTs for the co-located condition, yielding spatial benefit scores. In the research literature, the terms 'binaural intelligibility level difference' (e.g., Wolmarans et al., 2021) and 'spatial release from masking' (e.g., Peng et al., 2021) are also used for these measures.

Test Protocol

All participants attended two visits lasting for max. 60 minutes each. On average, the time interval between these two visits was 28.5 days. For each participant and condition, test–retest measurements were made. The test measurements took place at the first visit. The retest measurements were carried out at the second visit. If a given retest measurement deviated by more than 3 dB from the corresponding test measurement, a 'repeat' measurement was carried out. For the statistical analyses, the median of the test, retest and (if applicable) repeat measurements per participant and acoustic condition was calculated.

The first visit started with the tympanometry and audiometry, followed by the SRT measurements. The participants were orally instructed to repeat the two keywords in each sentence and to ignore the competing signals. If in doubt, they were encouraged to guess. To become familiar with the procedure, each participant completed two training SRTs (each based on one list of 20 sentences). The first SRT was measured without any masker (i.e., in quiet). The second SRT was measured with the same masker as used for the first condition following the training. A short break was given after the two training SRTs and whenever a participant appeared unfocused. The test lists and conditions were presented in random order across the participants. Different test lists were used for the test and retest measurements.

Statistical Analyses

The collected data were analyzed using SPSS (IBM) version 28. Initially, the raw data were inspected to identify unreliable measurements. To that end, the SD across the test, retest and (if appliable) repeat measurements of each participant was calculated. To identify outliers (i.e., datapoints exceeding 1.5 × the interquartile range of the corresponding dataset), boxplots of these SDs were then made for each age group and condition. Out of a total of 340 measured SRTs, three SRTs in the N0S0 condition, three SRTs in the N0S180 condition, and six SRTs in the spatially separated condition (from eight children and one adult) were identified as outliers and thus excluded. To examine the distribution of the resultant datasets, Shapiro–Wilk's test, normal Q-Q plots, histograms, and boxplots were made for the different age groups. These analyses revealed three datasets that were not normally distributed. To achieve normality for these datasets, one SRT from the N0S0 condition, one SRT from the N0S180 condition, and three SRTs from the co-located condition were also removed.

To assess the test–retest reliability of the remaining data, the within-subject SD, σ_w, the mean absolute SRT or benefit difference, $|\Delta SRT|$ or $|\Delta Benefit|$, and Pearson's correlation coefficient, r, were calculated for the test and retest measurements of all children and adults. Only participants with two measurements (test and retest) were included in this analysis.

To examine the influence of age and acoustic condition on the SRTs, a repeated-measures analysis of variance (ANOVA) with age group as between-subject factor (eight levels) and acoustic condition as within-subject factor (four levels) was performed. Because Mauchly's test indicated that the assumption of sphericity was violated for the factor 'acoustic condition', the Greenhouse–Geisser correction was applied to all related results. To examine the influence of age and type of measure on the benefit scores, a repeated-measures ANOVA with age group as between-subject factor (eight levels) and measure as within-subject factor (two levels) was performed. Both ANOVAs were based on the data from eight 6–7-year-olds, eight 7–8-year-olds, eight 8–9-year-olds, eleven 9–10-year-olds, eight 10–11-year-olds, nine 11–12-year-olds, eight 12–13-year-olds, and 16 adults, for whom complete datasets were available. Significant effects were followed up with planned contrasts or post hoc tests, and a significance level of 5% was used throughout.

In addition, linear regression analyses were carried out on the SRTs and benefit scores from the children. In this manner, prediction models for typically developing 6–13-year-olds were obtained. Age was entered as a continuous (rather than categorical) variable, with age being calculated as follows: number of years + number of months/12. The quality of each model was examined by checking the residuals, thereby confirming the assumptions of homoscedasticity and normality.

Finally, to examine the relation between binaural and spatial benefit, Pearson's correlation coefficient, r, was calculated based on the scores from the children and those from the adults.

Results

Descriptive Statistics

Table 1 provides a summary of the collected SRTs for the eight age groups and four acoustic conditions. For comparison, corresponding data for all children pooled together (age group 6–13) are also included. Figure 1 shows the mean SRTs together with 95% confidence intervals. In all acoustic conditions, mean SRTs decreased with higher age, with the adult group obtaining the lowest mean SRTs. For all age

Table 1. Descriptive Statistics for the SRTs Measured in the N0S0, N0S180, Co-Located, and Spatially Separated Conditions for the Different Age Groups. For Each Group and Condition, the Number of Participants (N), the Mean SRT (μ), the Minimum and Maximum SRT, and the Inter-Individual Standard Deviation (σ) are Shown. Corresponding Data for all Children Pooled Together (Age Group 6–13) are Also Included.

	SRT N0S0					SRT N0S180					SRT co-located					SRT spatially separated				
Age group	N	μ	min.	max.	σ	N	μ	min.	max.	σ	N	μ	min.	max.	σ	N	μ	min.	max.	σ
6–7	8	−1.9	−3.1	0.3	1.0	9	−4.3	−6.5	−0.7	2.1	9	−0.5	−4.2	3.6	2.6	9	−4.1	−6.6	−0.2	2.5
7–8	12	−2.3	−3.9	0.0	1.1	12	−5.9	−8.0	−3.1	1.5	10	0.3	−1.1	1.9	0.8	12	−4.9	−8.5	−0.8	2.4
8–9	9	−2.2	−4.3	−0.8	1.0	9	−5.8	−6.5	−4.8	0.5	10	−0.6	−4.4	1.7	1.8	10	−6.1	−11.0	−1.2	2.7
9–10	12	−2.7	−4.9	−0.8	1.4	12	−6.5	−10.0	−3.6	1.7	12	−2.1	−5.1	0.5	1.8	11	−5.8	−9.4	−2.5	2.5
10–11	9	−3.0	−4.8	−1.7	1.0	9	−7.0	−8.0	−5.3	1.1	9	−1.6	−7.6	1.9	2.7	8	−6.3	−9.5	−2.8	2.1
11–12	9	−2.8	−4.4	−1.5	1.0	9	−7.2	−9.0	−5.4	1.0	10	−1.4	−4.2	0.1	1.5	9	−7.0	−10.0	−5.2	1.5
12–13	10	−3.5	−5.5	−2.3	1.0	10	−7.8	−9.0	−6.0	1.2	10	−2.3	−7.2	0.0	2.0	8	−8.0	−9.5	−5.4	1.3
6–13	69	−2.7	−5.5	0.3	1.2	70	−6.3	−10.0	−0.7	1.7	70	−1.2	−7.6	3.6	2.1	67	−5.9	−11.0	−0.2	2.4
22–28	17	−4.4	−7.0	−2.7	1.2	16	−8.8	−12.0	−6.5	1.3	17	−6.5	−11.5	−1.0	3.2	17	−10.4	−13.6	−8.9	1.3

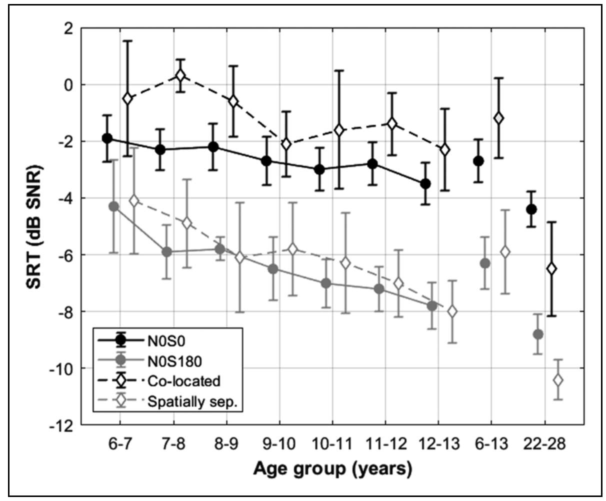

Figure 1. Mean SRTs with 95% confidence intervals for the four acoustic conditions and different age groups.

groups, mean SRTs were lower in the N0S180 and spatially separated conditions (where interaural difference cues were available) than in the N0S0 and co-located conditions (where no interaural difference cues were available). For the SRTs measured in stationary noise (N0S0 and N0S180 conditions), inter-individual differences were generally smaller than for the SRTs measured with speech maskers (co-located and spatially separated conditions). It is also worth noting that, in relative terms, the adults achieved lower SRTs with speech maskers (co-located and spatially separated) than with stationary noise (N0S0 and N0S180), whereas the children did not.

Table 2 provides a summary of the binaural and spatial benefit scores for the eight age groups, while Figure 2 shows corresponding mean scores with 95% confidence intervals. Again, the data from all children (age group 6–13) are shown for comparison. In terms of overall magnitude, the mean binaural and spatial benefit scores of the children and adults were all within 1 dB of each other (range: 3.8–4.8 dB). In terms of spread, there was a clear difference between the binaural and spatial benefit scores, with inter-individual standard deviations in many cases being at least twice as large for the spatial benefit scores (Table 2). Finally, while there was a trend for binaural benefit to increase with higher age (i.e., with >0.5 dB from 6–7 to 10–11 years and older), the same was not true for the spatial benefit scores which varied more across age.

Test–Retest Reliability

The results from the test–retest analysis are summarized in Table 3. For the SRTs measured in stationary noise (N0S0 and N0S180 conditions), the σ_w values were max. 1.0 dB SNR. For the SRTs measured with speech maskers (co-located and spatially separated conditions), the σ_w values were higher

Table 2. Descriptive Statistics for the Binaural and Spatial Benefit Scores for the Different Age Groups. For Each Group and Measure, the Number of Participants (N), the Mean Score (μ), the Minimum and Maximum Score, and the Inter-Individual Standard Deviation (σ) are Shown. Corresponding Data for all Children Pooled Together (Age Group 6–13) are also Included.

	Binaural benefit					Spatial benefit				
Age group	N	μ	min.	max.	σ	N	μ	min.	max.	σ
6–7	8	2.8	1.3	4.3	1.0	9	3.6	−2.2	8.8	3.7
7–8	11	3.7	1.7	6.2	1.4	9	6.1	4.0	8.8	1.6
8–9	8	3.4	0.5	4.8	1.5	10	5.5	0.6	10.0	2.9
9–10	12	3.8	1.9	5.1	1.0	11	3.5	0.2	7.9	2.6
10–11	9	3.9	1.3	5.3	1.3	8	4.3	−2.3	8.1	3.4
11–12	9	4.4	3.0	7.5	1.4	9	5.8	2.8	9.1	2.0
12–13	10	4.2	2.7	6.3	1.3	8	5.4	0.5	9.4	3.0
6–13	67	3.8	0.5	7.5	1.3	64	4.8	−2.3	10.0	2.8
22–28	16	4.5	1.8	7.2	1.4	17	3.9	−2.1	8.6	3.0

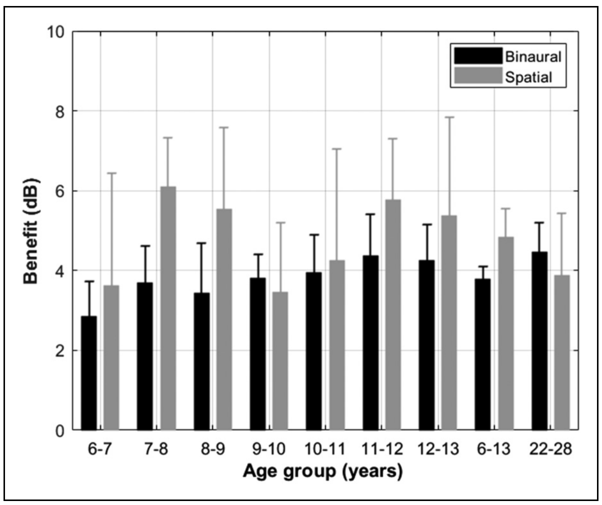

Figure 2. Mean binaural and spatial benefit scores with 95% confidence intervals for the different age groups.

Table 3. Results from the Test–Retest Analysis Performed on the SRTs and Benefit Scores of the Children and Adults. For Each Group and Outcome, the Available Sample Size (N), the Within-Subject Standard Deviation (σ_w), the Mean Absolute SRT Difference (|ΔSRT| or Benefit Difference |ΔBenefit|), and Pearson's Correlation Coefficient (r) are Shown. *: $p < .05$, **: $p < .01$, ***: $p < .001$.

Group	Measure	N	σ_w (dB SNR/dB)	|ΔSRT/ ΔBenefit| (dB)	r
Children	SRT N0S0	69	1.0	1.1	.62***
	SRT N0S180	60	1.0	1.1	.69***
	SRT co-located	39	1.2	1.5	.76***
	SRT spatially sep.	54	1.4	1.7	.69***
	Binaural benefit	58	1.2	1.3	.20
	Spatial benefit	31	1.9	2.2	.71***
Adults	SRT N0S0	15	0.9	0.8	.65**
	SRT N0S180	16	1.0	1.3	.50*
	SRT co-located	11	1.1	1.2	.93***
	SRT spatially sep.	10	0.9	1.1	.38
	Binaural benefit	15	1.5	1.7	.31
	Spatial benefit	8	1.5	1.9	.91**

for the children and comparable for the adults. The |ΔSRT| values were mostly around 1–1.5 dB, and the correlations were generally moderate to high. For the benefit scores, test–retest reliability was generally lower ($\sigma_w = 1.2$–1.9 dB; |ΔBenefit| = 1.3–2.2 dB). Furthermore, strong test–retest correlations were observed for the spatial benefit scores but not for the binaural benefit scores (Table 3).

Analyses of Variance

The ANOVA performed on the SRTs (without age group 6–13) showed significant effects of acoustic condition [$F(2.2, 146.2) = 188.8$, $p < .0001$] and age group [$F(7, 68) = 21.7$, $p < .0001$]. The interaction between these two factors was also significant [$F(15.0, 146.2) = 3.1$, $p < .001$]. Except for the N0S180 and spatially separated conditions ($p > .8$), all pairwise comparisons of the mean SRTs for the four acoustic conditions were significantly different (all $p < .01$). Post hoc testing with Bonferroni correction revealed a lower grand average SRT for the adults than for all other age groups (all $p < .001$). In addition, the children aged 12–13 years had a lower grand average SRT than the children aged 8–9 years or younger (all $p < .05$).

To follow up on the interaction between age group and acoustic condition, the ANOVA was initially repeated with the adults excluded. While the effects of acoustic condition [$F(2.2, 115.4) = 183.7$, $p < .0001$] and age group

[$F(6, 53) = 22.2$, $p < .001$] remained significant, their interaction did not ($p = .18$). Next, six planned contrasts were carried out on the child and adult data. These showed that, in relative terms, the adults obtained lower SRTs when presented with speech interferers (mean SRTs: −6.5 and −10.4 dB SNR for co-located and spatially separated) compared with speech-shaped noise (mean SRTs: −4.4 and −8.8 dB SNR for N0S0 and N0S180). In contrast, the children obtained higher SRTs in the presence of speech interferers (mean SRTs: −1.2 and −5.9 dB SNR for co-located and spatially separated) compared with speech-shaped noise (mean SRTs: −2.7 and −6.3 dB SNR for N0S0 and N0S180). Table 4 provides a summary of these results.

The ANOVA performed on the benefit scores (without age group 6–13) showed significant effects of age group [$F(7, 68) = 2.2$, $p = .045$] and measure [$F(1, 68) = 5.3$, $p = .024$]. The interaction of these two factors was not significant ($p > .27$). Post hoc testing based on Fisher's Least Significant Difference test revealed several pairwise differences (all $p < .05$) between the groups with the largest spatial benefit (i.e., groups 7–8, 8–9, 11–12, and 12–13) and the groups with the smallest spatial benefit (i.e., groups 6–7 and 9–10). A comparison of the two benefit measures revealed slightly higher spatial benefit scores (means: 3.8 vs. 4.7 dB).

Linear Regression Analyses

The results from the linear regression analyses are summarized in Table 5. Figures 3 and 4 show the four SRT and two benefit models in the form of scatter plots with least-squares regression lines and 95% confidence intervals based on the individual data points. As can be seen, the models for the spatially separated and N0S180 conditions have relatively steep slopes (−0.57 and −0.49 dB/year, respectively), whereas the models for the N0S0 and co-located conditions and especially the binaural and spatial benefit scores have shallower slopes (−0.23, −0.33, 0.20, and 0.15 dB/year, respectively). Moreover, the confidence intervals are narrowest for the N0S0 condition (approx. ±2 dB) and widest for the spatial benefit scores (approx. ±6 dB). It is also worth noting that, in contrast to the other models, the spatial benefit model was not statistically significant (Table 5).

Table 4. *P*-Values for Six Planned Contrasts Performed on the SRTs from Either the Children or the Adults to Follow Up on the Interaction Between Acoustic Condition and Age Group.

Planned contrasts	Children	Adults
N0S0 vs. N0S180	<.0001	<.0001
N0S0 vs. co-located	<.0001	.026
N0S0 vs. spatially sep.	<.0001	<.0001
N0S180 vs. co-located	<.0001	.014
N0S180 vs. spatially sep.	.52	.001
Co-located vs. spatially sep.	<.0001	<.001

Binaural Versus Spatial Benefit

Correlating the binaural and spatial benefit scores of the children with each other revealed no relation between these two datasets ($N = 67$, $r = .01$, $p = .97$). While the same was true for the adults, a tendency for their scores to be moderately correlated emerged ($N = 16$, $r = .48$, $p = .059$).

Discussion

Influence of age

As expected, mean SRTs decreased with higher age in all acoustic conditions, with the adults generally outperforming the children (Table 1 and Figure 1). The oldest children (group 12–13), however, performed on a par with the adults in all but the co-located condition (Table 3). Furthermore, the 10–11-year-olds achieved adult-like performance in the N0S0 condition. The same was true for the 11–12-year-olds in the N0S180 condition. Broadly speaking, these results are in concordance with previous studies reporting adult-like performance around 10–12 years of age (e.g., Hjertman et al., 2021; Vaillancourt et al., 2008; Wilson et al., 2010). Nevertheless, not even the oldest children tested here (group 12–13) managed to achieve adult-like results in the co-located condition. Arguably, the segregation of concurrent talkers is a complex task that requires mature auditory skills, especially when the acoustic information available for teasing different voices apart is sparse. It is also possible that young children require more acoustic/phonetic information to recognize speech than older children or adults. Interestingly, the adult participants showed markedly

Table 5. Results from the Linear Regression Analyses Performed on the Data from the Children with SRT or Benefit Score as Dependent Variable and Age as Independent variable. *P*-Values are Shown for the Full Model, the Intercept, and the Predictor (Age).

Measure	Model	R^2 (adjusted)	p_{model}	$p_{intercept}$	p_{age}
SRT N0S0	−0.45 − 0.23 × age	.16 (.15)	<.001	.48	<.001
SRT N0S180	−1.76 − 0.49 × age	.33 (.32)	<.0001	.032	<.0001
SRT co-located	1.89 − 0.33 × age	.10 (.09)	<.01	.10	<.01
SRT spat. sep.	−0.63 − 0.57 × age	.22 (.21)	<.0001	.62	<.0001
Binaural benefit	1.86 + 0.20 × age	.10 (.09)	<.01	.013	<.01
Spatial benefit	3.41 + 0.15 × age	.01 (.00)	.40	.053	.40

larger inter-individual differences in the co-located condition compared with the other conditions (Table 1 and Figure 1). This is consistent with the finding that difficulties with segregating multiple speech signals can persist into adulthood, which will be discussed further below.

Influence of Acoustic Condition

As expected, mean SRTs were lower in the N0S180 and spatially separated conditions than in the N0S0 and co-located conditions (Table 1 and Figure 1). This was true for all groups tested here, thereby illustrating the importance of binaural hearing abilities for speech-in-noise perception.

The type of masker signal is also known to influence speech recognition performance. If a fluctuating rather than stationary masker is used, this will allow for glimpsing to occur (e.g., Cooke, 2006). Adults can take advantage of brief glimpses of target speech during dips in the amplitude envelope of fluctuating maskers and thereby achieve better performance, whereas young children show immature glimpsing abilities (Leibold & Buss, 2019). If a speech masker instead of a noise masker is used, this can also impact performance. This is because speech maskers cause informational masking that can interfere with perceptual grouping and selective attention mechanisms (e.g., Kidd et al., 2008). Research has shown that extensive listening

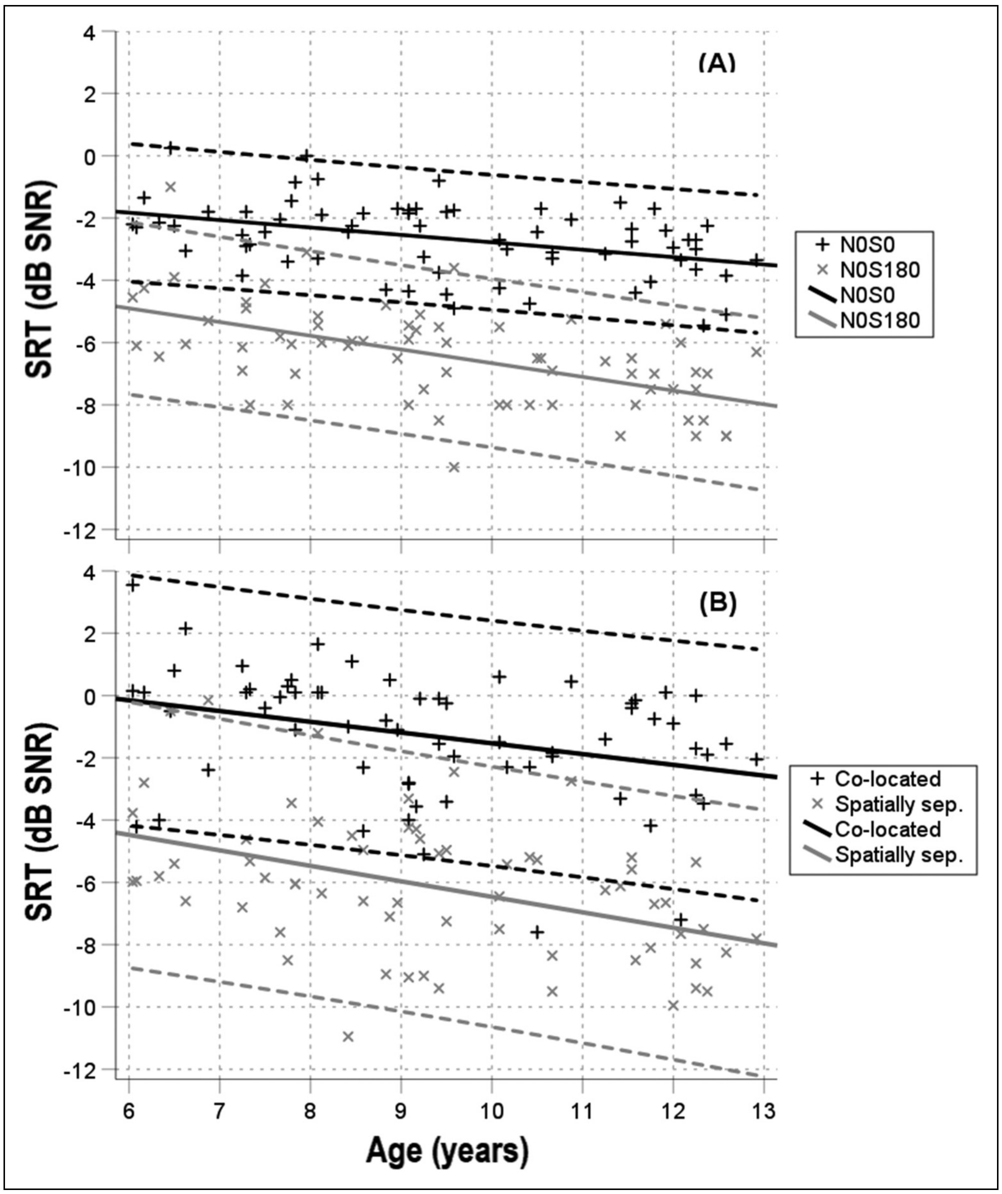

Figure 3. Scatter plots with least-squares regression lines (solid lines) and 95% confidence intervals based on the individual data points of the children (dashed lines). (A) N0S0 (black, + symbols) and N0S180 (grey, × symbols) conditions. (B) Co-located (black, + symbols) and spatially separated (grey, × symbols) conditions.

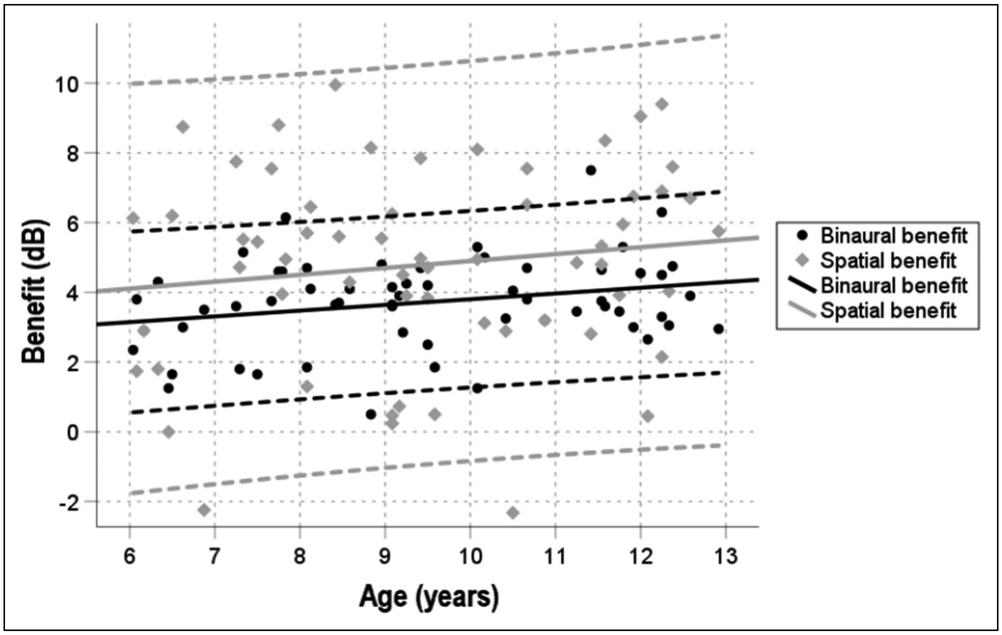

Figure 4. Scatter plots with least-squares regression lines (solid lines) and 95% confidence intervals based on the individual data points of the children (dashed lines) for the binaural (black, + symbols) and spatial (grey, × symbols) benefit measures.

experience is required for mature grouping and attention abilities to emerge, and so their development typically persists into adolescence (Leibold & Buss, 2019).

Accordingly, Buss et al. (2016) found that children performed worse on a speech recognition task when speech rather than speech-shaped noise was used as masker. Likewise, the children tested here obtained higher SRTs in the conditions with speech maskers ($SRT_{N0S0} < SRT_{co-loc}$ and $SRT_{N0S180} < SRT_{spat\_sep}$). For the adults, on the other hand, SRTs were generally lower when speech maskers were used ($SRT_{N0S0} > SRT_{co-loc}$ and $SRT_{N0S180} > SRT_{spat\_sep}$). As mentioned above, complex perceptual abilities are needed for segregating concurrent speech signals. Since these abilities still need to develop in school-age children, this can explain why the children and adults tested here showed different SRT patterns.

Psychometric Properties

The current study also evaluated the test–retest reliability of the different measurements. Reliability was high for the SRTs in stationary speech-shaped noise ($\sigma_w = 0.9$–1.0 dB SNR). Also, for the N0S0 condition a mean SRT of −2.7 dB SNR was obtained. Overall, these results are in very good agreement with those of Koiek et al. (2020) and speak for good reproducibility of these measurements. For the two benefit measures, on the other hand, reliability was lower, especially for the spatial benefit scores ($\sigma_w = 1.5$–1.9 dB). This finding could be one reason why some of the results were unexpected, as discussed below.

For clinical applications, the performance of typically developing children on a given speech test needs to be known. The regression models that were built (Table 5) allow typical performance to be predicted. The models indicate larger improvements with higher age in the conditions where interaural difference cues are available. Furthermore, they indicate larger improvements with higher age when speech maskers are used. These results, which are consistent with previous findings (e.g., Leibold & Buss, 2019; Wolmarans et al., 2021), confirm that the mechanisms underlying binaural processing and talker segregation develop substantially during childhood.

It is also worth noting that, compared to other pediatric speech tests, the SRTs obtained here were notably higher. Overall, the children tested here obtained SRTs of −2.7 dB SNR (N0S0), −6.3 dB SNR (N0S180), −1.2 dB SNR (co-located), and −5.9 dB SNR (spatially separated). For their digits-in-noise test, Wolmarans et al. (2021) obtained mean SRTs of −9.2 dB SNR (N0S0) and −16.4 dB SNR (N0S180). For the LISN-S with three different female voices, Cameron and Dillon (2007) obtained mean SRTs of −4.1 dB SNR (co-located) and −13.4 dB SNR (spatially separated). Presumably, the higher SRTs found here are due to the open-set nature of the DAT materials, which makes it virtually impossible for listeners to learn the 'test vocabulary'. This, in turn, reduces the influence of top-down mechanisms on performance, resulting in higher test SNRs that arguably are more representative of the SNRs encountered in real-world listening environments (Smeds et al., 2015).

Binaural Versus Spatial Benefit

The current study also examined benefit from interaural difference cues in school-age children. As mentioned above, previous research has shown that binaural hearing develops significantly during childhood, with performance on some binaural listening tasks reaching adult levels around 10–12 years of age (Flanagan et al., 2021; Wolmarans et al., 2021). To a first approximation, the binaural benefit scores from the current study are consistent with this. That is, the results showed a trend for binaural benefit to increase from age 6–7 to age 10–11 and above (Figure 2). The same was not true for the spatial benefit scores, which varied more across the different age groups. In general, due to the differential nature of any benefit measure more variability compared to, for example, SRTs is to be expected. The test–retest analysis reported above had revealed higher reliability for the SRTs in stationary noise than those in competing speech (Table 3). The clearer age effects observed in the binaural benefit scores are likely a reflection of this.

The fact that the mean benefit scores were similar in magnitude for both measures and participant groups (range: 3.8–4.8 dB; Table 2) also requires some discussion. As mentioned in the Introduction, using a smartphone-based digits-in-noise test Wolmarans et al. (2021) observed a mean binaural benefit of approximately 7 dB in 6–14-year-olds. Koopmans et al. (2018), who performed very similar measurements under more controlled conditions, observed a mean binaural benefit of approximately 4 dB in 4–12-year-olds and of approximately 5 dB in young adults. While the results of Koopmans et al. (2018) are in close agreement with the ones reported here, those of Wolmarans et al. (2021) are not. This discrepancy could be related to the way the tests were implemented and administered in the different studies. As also mentioned in the Introduction, for the LISN-N Cameron and Dillon (2007) observed a mean spatial benefit of approximately 9 dB in 5–11-year-olds and an age dependency. Clearly, these results diverge from the ones reported here. Again, the lower reliability of the spatial benefit scores could have played a role. Another explanation could be larger differences in the voice characteristics (e.g., in terms of pitch, intonation, or speed) of the three competing talkers used here as compared with the LISN-N. When such differences are more pronounced, spatial cues contribute less to task performance and offer therefore less benefit (e.g., Bronkhorst, 2015; Darwin, 2006). Further research will be required to resolve the observed discrepancies.

The lack of a correlation between the binaural and spatial benefit scores could be due to the data being 'noisy' or the two measures tapping into different perceptual abilities. The latter would be consistent with previous research showing different patterns in terms of individual differences for speech-in-noise and speech-on-speech tasks (e.g., Buss et al., 2021; Goldsworthy & Markle, 2019). As discussed above, speech-on-speech tasks require complex grouping and attentional abilities that typically first mature during adolescence. The trend for a moderate correlation between the scores of the adults observed above (see Binaural Versus Spatial Benefit) could be indicative of the underlying mechanisms becoming more aligned with higher age. From a clinical perspective, the better repeatability of the binaural benefit scores speaks in their favor. However, compared to speech-in-noise tasks, speech-on-speech tasks typically elicit larger inter-individual differences (see Tables 1 and 2) and may better predict the functional hearing abilities of children (e.g., Corbin et al., 2021; Hillock-Dunn et al., 2015). Thus, when choosing a measure for clinical testing different factors need to be considered.

As a side remark, the co-located and spatially separated conditions were implemented using generic head-related impulse responses measured on a KEMAR dummy-head, as also done in the LISN-N (Cameron & Dillon, 2007). Braren and Fels (2021) recently published a database containing corresponding measurements made on 5–10-year-olds as well as on KEMAR. A comparison of their child and KEMAR data shows that low-frequency interaural time differences are similar in magnitude, whereas high-frequency monaural spectral cues are much more variable in 5–10-year-olds (see Figures 6–7 in Braren & Fels, 2021). Nevertheless, high-frequency interaural level differences appear similar in overall magnitude. Thus, while the use of head-related impulse responses tailored to the children tested here could have produced different results in the co-located and spatially separated conditions, large differences seem unlikely.

Conclusion

Using the validated sentence lists from the børneDAT corpus, the current study collected normative speech recognition data from participants aged 6–13 and 22–28 years in conditions with and without interaural difference cues. The analyses confirmed that around 12–13 years of age children can achieve adult-like performance on many speech tasks. Nevertheless, the children tested here seemed unable to take advantage of glimpsing opportunities and/or were more affected by informational masking effects when presented with two running speech maskers instead of stationary noise (unlike the adults). Test–retest reliability was found to be highest for the SRTs measured in stationary noise and lowest for the spatial benefit scores. The latter finding might explain why spatial and binaural benefit were comparable in magnitude, why age effects were absent in the spatial benefit scores, and why the binaural and spatial benefit scores were not correlated. Alternatively, the latter finding could indicate that the two benefit measures tap into different perceptual mechanisms.

In summary, the current study produced reference data for the Danish børneDAT corpus for normal-hearing 6–13-year-olds and young adults who were tested in different acoustic conditions. These data can be of value for future research and clinical applications.

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