

Research paper

Individual differences in speech-in-noise perception parallel neural speech processing and attention in preschoolers



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ABSTRACT

From bustling classrooms to unruly lunchrooms, school settings are noisy. To learn effectively in the unwelcome company of numerous distractions, children must clearly perceive speech in noise. In older children and adults, speech-in-noise perception is supported by sensory and cognitive processes, but the correlates underlying this critical listening skill in young children (3–5 year olds) remain undetermined. Employing a longitudinal design (two evaluations separated by ~12 months), we followed a cohort of 59 preschoolers, ages 3.0–4.9, assessing word-in-noise perception, cognitive abilities (intelligence, short-term memory, attention), and neural responses to speech. Results reveal changes in word-in-noise perception parallel changes in processing of the fundamental frequency (F0), an acoustic cue known for playing a role central to speaker identification and auditory scene analysis. Four unique developmental trajectories (speech-in-noise perception groups) confirm this relationship, in that improvements and declines in word-in-noise perception couple with enhancements and diminishments of F0 encoding, respectively. Improvements in word-in-noise perception also pair with gains in attention. Word-in-noise perception does not relate to strength of neural harmonic representation or short-term memory. These findings reinforce previously-reported roles of F0 and attention in hearing speech in noise in older children and adults, and extend this relationship to preschool children.

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1. Introduction

The classroom environment, a child's gateway to learning, seldom offers pristine listening conditions. School settings often exceed recommended noise levels (Bradley and Sato, 2008; Summers and Leek, 1998), and this interference can compromise a student's reading performance, information retention, and academic motivation (Shield and Dockrell, 2008). Absorbing a

teacher's input despite the scraping of chairs and the chattering of classmates requires that students effectively perceive speech in the presence of background noise. While speech-in-noise perception plays an important role in classroom learning, the mechanisms supporting speech-in-noise perception in children at the start of formal schooling (i.e., preschool and kindergarten) are under debate.

Young children experience substantially greater difficulty perceiving speech in noise than older children and adults (Elliott, 1979; Litovsky, 2005). Young children may be particularly challenged to understand speech in noise because of factors that hinder overall auditory perception, such as relatively heightened internal noise and reduced intrinsic attention (Buss et al., 2006, 2009; Moore et al., 2010). As both subside with development, these factors are considered characteristics of an under-developed nervous system. Moreover, studies in adults show that speech-in-noise perception is a complex task that simultaneously requires

Abbreviations: FFR, frequency-following response; ABR, auditory brainstem response; F0, fundamental frequency; M, mean; SD, standard deviation; SRT, speech reception threshold; SNR, signal-to-noise ratio; CRISP, Children's Realistic Index of Speech Perception; ME, main effect; IXN, interaction; STM, short-term memory

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integration of sensory processing, attention, memory, and linguistic knowledge (Anderson et al., 2013a; Garadat and Litovsky, 2007; Kalikow and Stevens, 1977; Song et al., 2011; Werner et al., 2012; Zheng et al., 2013), all of which remain under development in preschoolers.

Speech-in-noise perception relies upon the listener's ability to separate the target signal from competing inputs. Certain acoustic cues, such as the fundamental frequency (F0), assist this process by providing information for grouping auditory features into objects and identifying a speaker's voice (Andreou et al., 2011; Shamma et al., 2011; Summers and Leek, 1998). In older children and adults, biological processes, such as enhanced neural representation of the F0, are presumed to be important for speech perception in noise (Anderson et al., 2010; Song et al., 2011). In this older cohort, speech perception in noise additionally relies upon a number of cognitive and linguistic factors including selective attention, short-term memory, and lexical knowledge (Lewis et al., 2010; Pichora-Fuller et al., 1995). While there is reason to believe that these phenomena extend to preschoolers, this has yet to be tested.

To investigate the biological and cognitive processes supporting hearing in noise in early childhood, and to determine the influence of individual differences and development on these processes, we assessed young children (3 and 4 years old) on speech-in-noise perception, cognitive skills (intelligence, short-term memory, and attention), and frequency-following responses (FFR) to speech longitudinally for one year (two time points separated by ~12 months). We hypothesized that if speech-in-noise perception hinges upon neural representation of sound and cognitive abilities, then individual variability of speech-in-noise perception reflects the strength of these components and the effectiveness of their integration. We predict changes on the speech-in-noise task will be associated with changes in neural function and cognition: robust representation of speech acoustic cues (F0), attention, and memory performance will track with improved perception of speech in noise.

2. Material and methods

2.1. Participants

Fifty-nine children, (30 females), ages three and four years (Range = 3.0–4.9, $M = 4.18$, $SD = 0.57$), were recruited from the Chicago area. Children were monolingual-English speakers with no history of a neurological disorder. Ten children had a family history of a language, learning, or attention disorder (e.g. parent with dyslexia; see Table 1), but only one child had a formal diagnosis. The exclusion of this child did not change the results, so they were included in the reported analyses. All children passed a screening of peripheral auditory function (normal otoscopy, Type A tympanograms, distortion product otoacoustic emissions ≥ 6 dB

SPL above the noise floor from 1 to 8 kHz) and had click-evoked auditory brainstem responses within normal limits (wave V latency < 6 ms). Verbal assent was obtained from the children, and written consent was obtained from their parents and/or guardians. Northwestern University's Institutional Review Board approved all experimental procedures, and testing was carried out in accordance to these guidelines. All participants were remunerated for their participation.

2.2. Testing

Assessments were completed at two time points: once when children were either 3 or 4 years old, and again twelve months following their initial visit, when they were 4 or 5 years old.

2.3. Intelligence, sustained attention, and short-term memory

Verbal and non-verbal intelligence was assessed using the Wechsler's Preschool and Primary Scale of Intelligence (WPPSI; Information, Object Assembly and Matrix Reasoning subtests; Wechsler, 2002). In the first year, Information (verbal intelligence) and either Object Assembly (3 y.o.) or Matrix Reasoning (4 y.o.) subtests (non-verbal intelligence) were used. These two non-verbal subtests were chosen based on their test reliability for each age group. In the second year, the subtests Information (verbal intelligence) and Matrix Reasoning (non-verbal intelligence) were used. Sustained attention was measured using the Leiter-R subtest of Attention Sustained (Roid and Miller, 1997). In this test, a child was presented with a page filled with images, and was non-verbally encouraged to mark a target image (e.g., flower) amongst distracter images (e.g., butterflies, ladybugs, stars). Attention sustained scores are comprised of total correctly circled targets within the limited time frame. Short-term memory (STM) was evaluated using the Children's Evaluation of Language Fluency (CELF-P2; Wiig et al., 2004) subtest of Recalling Sentences, in both years. In this test, each child was asked to repeat sentences of increasing length and complexity. Raw scores of the cognitive tests were used due to limitations in age-normed scores; for these analyses, age was used as a covariate.

2.4. Speech-in-noise perception

The Children's Realistic Index of Speech Perception (CRISP; Litovsky, 2005), a pediatric words-in-noise perception task, was used to obtain speech reception thresholds (SRTs) in free-field. Each child was seated in a chair three feet from a wall-mounted speaker and instructed to look at the front speaker and listen for the word spoken by a male speaker, although two women would be speaking sentences in the background. The target words (spondee compound nouns) were spoken by a male at an initial level of 60 dB SPL, and adapted in level according to the child's response accuracy. The

Table 1
List of participants with reported family history of language-based learning disability.

	Group	Family history	Diagnosis
1	Reverse	Father (dyslexia)	No
2	Low Performers	Father (dyslexia)	No
3	Reverse	Sibling (articulation/pragmatic language delays; central auditory processing disorder)	No
4	Catch-up	Sister (ASD)	No
5	Reverse	Father (dyslexia), sibling (learning, reading delays), sibling (speech, learning, reading delays)	No
6	Low Performers	Twin (speech delay, non-diagnosed)	Yes; speech delay and ADHD
7	Reverse	Twin (speech delay and ADHD)	No
8	Reverse	Mother (dyslexia), sibling (dyslexia), grandparent (dyslexia)	No
9	Low Performers	Sibling (speech, learning, reading delays)	No
10	Low Performers	Twin (speech, learning delays)	No

competitor noise consisted of two female talkers speaking semantically meaningful sentences (fixed at 55 dB), and was presented with the target signals from the same front speaker (0° Azimuth). A four-alternative forced visual choice paradigm was presented after each word, and the child was asked to point to the picture of the word they heard. To eliminate a potential confound of vocabulary size, the test was preceded by a familiarization phase whereby children heard and repeated the name of each picture, then identified the pictures in isolation, with incorrectly or unidentified pictures excluded from the test. Thus, the total number of potential words used for testing was different for each child (Year 1: Mean = 20.41, SD = 3.779, Range = 11–25; Year 2: Mean = 21.83, SD = 3.13, Range = 12–25). Four reversals occurred throughout the test, with the final SRT calculated as an average of the last two reversals. The adaptive tracking procedure, described in greater detail in Litovsky (2005), follows a set of rules to vary the target signal through a modified adaptive three-down/one-up algorithm.

2.5. Speech-in-noise profiles

While the ability to perceive speech in noise improved for most children over the course of a year, some children's thresholds did not change, while others regressed. To characterize these variations, children were divided into four groups based on their SRT signal-to-noise ratio [SNR; dB level of signal (target word) minus dB level of noise (background talkers), where an SNR of 0 would be level of signal = level of noise] across the two assessments. The first group, the High Performers ($n = 14$), performed well in both years, demonstrating mostly negative SRT signal-to-noise ratios (i.e., signal < noise) at both time-points. The second group, the Low Performers ($n = 17$), performed poorly in both years, with mostly positive SRT signal-to-noise ratios (i.e., signal > noise) at both time-points. The third group, the Catch-up group ($n = 10$), was characterized by a significant improvement over time (i.e., SRT difference greater than 7 dB), in which they had positive SRT signal-to-noise ratios at the first assessment, and negative SRT signal-to-noise ratios at the second assessment. The fourth group, the Reverse group ($n = 18$), regressed over time; the Reverse group had negative SRT signal-to-noise ratios at the first assessment, but positive SRT signal-to-noise ratios at the second assessment. Groups were balanced for sex, age, and intelligence (verbal or nonverbal) in both years (*sex*: $F(3,56) = 0.758$, $p = 0.522$; *age year 1*: $F(3,56) = 0.987$, $p = 0.406$; *age year 2*: $F(3,56) = 1.533$, $p = 0.216$; *verbal intelligence year 1*: $F(3,56) = 0.754$, $p = 0.525$; *verbal intelligence year 2*: $F(3,56) = 0.175$, $p = 0.913$; *non-verbal intelligence year 1*: $F(3,56) = 0.377$, $p = 0.770$; *non-verbal intelligence year 2*: $F(3,56) = 0.505$, $p = 0.680$). In addition, the groups did not differ in maternal or paternal education levels (*maternal*: $F(3,55) = 1.277$, $p = 0.292$; *paternal*: $F(3,55) = 1.668$, $p = 0.185$), nor years of schooling ($F(3,55) = 0.800$, $p = 0.499$; N.B. one family did not report education levels). See Table 2 for additional details on the groups.

2.6. Identification of variable speech-in-noise performance: waning intrinsic attention?

Intrinsic attention may influence auditory perceptual task

performance, especially in young childhood. While most children are able to complete a perceptual task (e.g., frequency detection, gap detection) with ease, others have difficulty sustaining attention over time. Previous reports have suggested that some children “trail off” during a task perhaps due to insufficient intrinsic attention (Barry et al., 2010). To investigate intrinsic attention in this dataset, we generated trial-by-trial variability plots for the speech-in-noise test for all children, and calculated the change in intensity over the last half of each child's testing session. To do this, change in intensity from trial to trial was summed over the second half of trials for each child. Because a decrease in intensity or no change follows a correct answer, and an increase in intensity follows an incorrect answer, we interpret large, positive numbers to signify more incorrect answers in the second half of the testing session. Representative figures are illustrated in Fig. 1.

2.7. Electrophysiological assessment

Frequency following responses (FFRs), also known as auditory brainstem responses to complex sounds (cABR; Skoe and Kraus, 2010), were elicited by a 170 ms [da] stimulus embedded in background babble, and collected using a BioSEMI Active2 recording system with an auditory brainstem response module. In all, 4200 sweeps were collected. The speech syllable [da], constructed with a Klatt-based synthesizer at 20 kHz, is a voiced six-formant stop consonant with a fundamental frequency of 100 Hz; during the consonant-vowel transition (0–50 ms) the lower three formants shift (f_1 : 400–720 Hz, f_2 : 1700–1240 Hz, f_3 : 2580–2500 Hz), while the fundamental frequency and upper three formants are steady (F_0 : 100 Hz, F_4 : 3300 Hz, F_5 : 3750 Hz, F_6 : 4900 Hz). During the vowel /a/ portion of the stimulus (50–170 ms), the six formants do not fluctuate.

The [da] stimulus was presented against a six-talker babble track (3 female speakers; length of 4000 ms; semantically-anomalous English sentences) at a +10 dB SNR. The noise track was looped continuously to prevent phase synchrony between onsets of the [da] and the noise. The [da] and noise were mixed into a single channel and presented monaurally to the right ear at 80 dB SPL (the babble, on average, was presented at 70 dB SPL) through electromagnetically-shielded insert earphones (ER-3A, Etymotic Research, Elk Grove Village, IL, USA) in alternating polarities.

During the recording, children sat in a comfortable chair within an electrically-shielded and sound-attenuated booth (IAC Acoustics, Bronx, NY, USA), and watched a film of their choice. The left ear was left unoccluded so the child could hear the soundtrack of the movie (<40 dB SPL). Electrodes were placed at Cz for active non-inverting, right and left earlobes for inverting references (unlinked), and ± 1 cm on either side of Fpz for grounding (CMS/DRL). All offsets were kept below 50 mV.

Within the BioSEMI ActiABR module for LabView 2.0 (National Instruments, Austin, TX, USA), the responses were online filtered 100–3000 Hz (20 dB/decade roll-off), and digitized at 16.384 kHz. Offline amplification in the frequency domain was performed to open the high pass to 0.1 Hz in MATLAB (The Mathworks, Inc., Natick, MA, USA) using custom software. Responses were then

Table 2
Descriptive statistics of the speech-in-noise groups.

Group	N	Age (Years, SD)	CRISP Year 1 (SNR)	CRISP Year 2 (SNR)
High performers	14 (7F)	4.3 (0.5)	−2.8 (3.8)	−4.6 (2.3)
Low performers	17 (11F)	4.0 (0.6)	4.1 (2.6)	1.4 (2.3)
Catch-up	10 (5F)	4.2 (0.5)	3.1 (2.6)	−5.2 (2.7)
Reverse	18 (7F)	4.2 (0.7)	−1.9 (3.5)	2.0 (2.6)

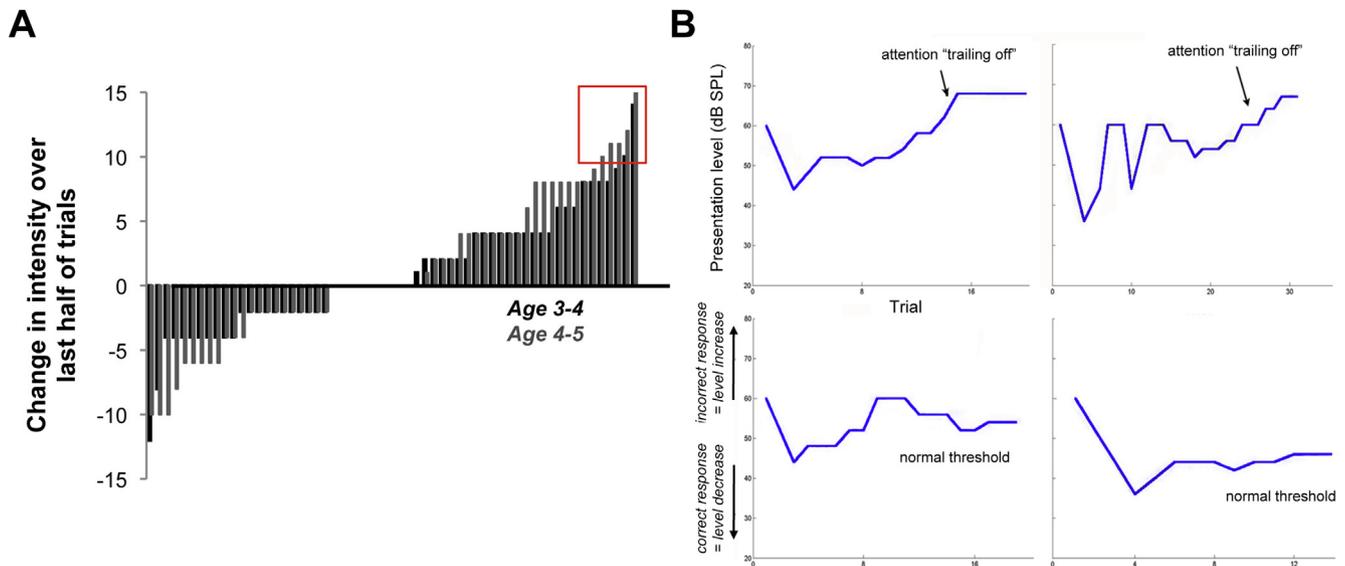


Fig. 1. [A] A quantitative analysis of intrinsic attention was performed by calculating the change in signal presentation intensity over the last half of each child's CRISP session. A distribution of the change scores is plotted (Fig. 1A), and 7 children fell 2 standard deviations outside of the mean (Fig. 1A, red box). These children were identified for a potential "trail off" in their ability to attend during the end of the task. [B] The majority of these children were in the "Reverse" and "Low Performers" groups; Fig. 1B, top panels, demonstrate plots from children in the Reverse (left) and Low Performers (right) groups. In comparison, threshold estimation for children who were attending throughout the task (Fig. 1B: bottom panels), demonstrate varying level reductions and increments. In these cases, the adaptive tracking method appropriately narrowed in on the child's speech reception threshold. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

bandpass filtered to the frequency region of interest (70–2000 Hz, Butterworth filter, 12 dB/octave roll-off, zero phase shift), epoched from –40 to 210 ms (stimulus onset at 0 ms), baselined, and artifact rejected ($\pm 35 \mu\text{V}$). Responses to alternating polarities were added to emphasize the stimulus envelope (FFR_{ENV} ; fundamental frequency analyses) and subtracted to emphasize the temporal fine structure (FFR_{TFS} ; harmonics analyses) (Aiken and Picton, 2008; Skoe and Kraus, 2010).

Spectral amplitudes of the fundamental frequency (F0) and each harmonic were extracted. A composite measure was created for harmonic amplitude by collapsing across harmonics H2–H10. Because the frequency-following response is remarkably identical to the signal that evokes it, we interpret larger amplitudes to indicate a more robust representation of these acoustic cues. Please see Fig. 2 for response averages in the temporal and spectral domains.

2.8. Statistical analyses

To analyze year-to-year change in speech-in-noise perception, F0 amplitude, harmonics amplitude, short-term memory, and attention, we first calculated change between assessments by subtracting the first year (y_1) from the second (y_2) for speech-in-noise perception ($\Delta\text{CRISP} = y_2 \text{ CRISP} - y_1 \text{ CRISP}$), F0 amplitude ($\Delta\text{F0} = y_2 \text{ F0} - y_1 \text{ F0}$), harmonics amplitude ($\Delta\text{Harmonics} = y_2 \text{ Harmonics} - y_1 \text{ Harmonics}$), verbal intelligence ($\Delta\text{Intelligence}_{\text{verbal}} = y_2 \text{ Intelligence}_{\text{verbal}} - y_1 \text{ Intelligence}_{\text{verbal}}$), non-verbal intelligence ($\Delta\text{Intelligence}_{\text{non-verbal}} = y_2 \text{ Intelligence}_{\text{non-verbal}} - y_1 \text{ Intelligence}_{\text{non-verbal}}$), attention ($\Delta\text{Attention} = y_2 \text{ Attention} - y_1 \text{ Attention}$) and short-term memory ($\Delta\text{STM} = y_2 \text{ STM} - y_1 \text{ STM}$). Pearson's correlations were used to determine relationships between change in CRISP and change in F0, harmonics, short-term memory, and attention along a continuum. To determine demographic differences between the four speech-in-noise perception groups, one-way analysis of variance (ANOVA) comparisons were used to compare sex, age, and intelligence (verbal

and nonverbal). To reinforce the correlation analyses, and to analyze how unique developmental trajectories changed in processing of the F0, harmonics, short-term memory, and attention over time, we ran four separate two-way, 4 (group) \times 2 (year of test) repeated measures ANOVAs. Follow-up t-tests were Bonferroni corrected.

3. Results

Speech-in-noise performance improved within the relatively short developmental window of one year (Fig. 3). As children matured, performance improved (main effect (ME) of year: $F(1,58) = 44.787$, $p < 0.001$; Fig. 3A). We also found four distinct trajectories of speech-in-noise perception exist within this large cohort: High Performers, Low Performers, Catch-up, and Reverse groups differed in year-to-year changes for speech-in-noise performance (group \times year interaction (IXN): $F(3,56) = 51.362$, $p < 0.001$; Fig. 3B–C).

We then asked if changes in speech-in-noise perception parallel changes in brain function (processing of the F0 and harmonics). Over time, improvements and declines in speech-in-noise were associated with F0 enhancements and degradations, respectively ($r(59) = -0.402$, $p = 0.002$; Fig. 4A; FFR_{ENV}). To follow-up on this correlation, we looked at relationships between these two variables at each time point; at age 3–4 years old, there was no significant relationship between hearing in noise and F0 ($r(59) = -0.101$, $p = 0.448$, Fig. 4B), yet one year later, when the children were 4–5 years old, a significant relationship emerged ($r(59) = -0.299$, $p = 0.022$, Fig. 4C). Next, we looked at the four distinct trajectories of speech-in-noise perception, and assessed their changes in processing of the F0 over time. Among the four speech-in-noise perception groups, unique year-to-year changes in F0 encoding emerged (IXN: $F(3,56) = 6.944$, $p < 0.001$; Fig. 4D–F; ME group: $F(3,56) = 1.043$, $p = 0.381$; ME year: $F(1,58) = 2.215$, $p = 0.142$). F0 enhancements were present in the High Performers, Low Performers, and Catch-up groups, while F0 degradations were

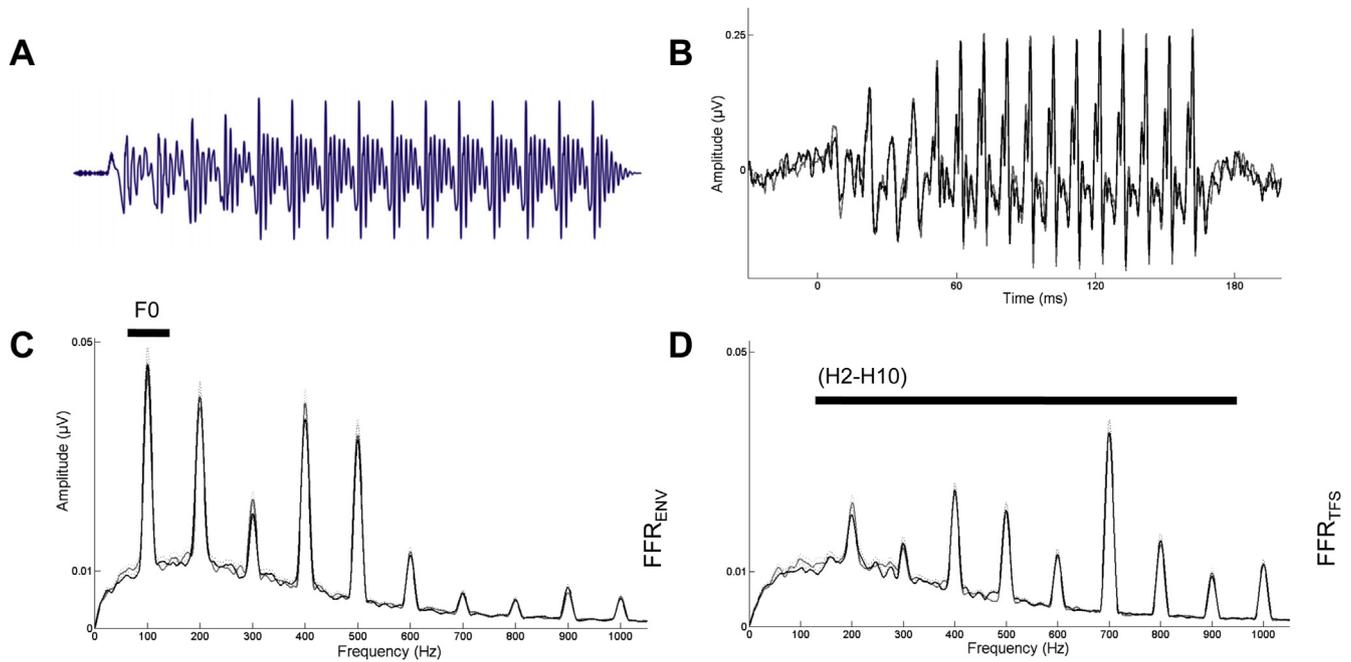


Fig. 2. [A] Frequency following responses were collected to the [da] stimulus, seen here, presented in background babble. The grand average response is illustrated for year 1 (black) and year 2 (grey) for the following: [B] time domain (FFR_{ENV}), [C] spectra to emphasize the envelope (FFR_{ENV}), and [D] spectra to emphasize the temporal fine structure (FFR_{TFS}).

observed for the Reverse group. Follow-up comparisons revealed significant F0 enhancements from year 1 to year 2 for the Catch-up group ($t(10) = -3.32$, $p = 0.009$), and large F0 decrements in the Reverse group ($t(18) = 3.24$, $p = 0.005$). F0 enhancements were also observed in the High Performers and Low Performers, but these year-to-year changes were not significant (High Performers: $t(14) = -1.65$, $p = 0.122$; Low Performers: $t(17) = -0.975$, $p = 0.344$).

Unlike the F0 results, we did not see a relationship between speech-in-noise changes and harmonic changes ($r(59) = -0.091$, $p = 0.495$; Fig. 5B; FFR_{TFS}). Furthermore, we did not see evidence of distinct harmonic encoding by the four groups (IXN: $F(3,56) = 1.05$, $p = 0.378$; Fig. 5A and C), nor overall year-to-year changes (ME year: $F(1,58) = 0.003$, $p = 0.960$) or a group difference (ME group: $F(3,56) = 1.093$, $p = 0.36$).

Next, we asked if changes in speech-in-noise perception parallel changes in cognitive function (sustained attention and short-term memory). Overall, children improved in sustained attention from year to year (ME year: $F(1,58) = 12.797$, $p = 0.001$). Although we did not see a pattern between changes in speech-in-noise and changes in attention across all individuals, we did see a relationship when only including the children who improved on hearing in noise (i.e., excluding the Reverse group); improvements in attention related to improvements in speech-in-noise performance ($r(38) = -0.446$, $p = 0.004$; Fig. 6B; because the Reverse group demonstrated an increase in attention despite a decrease in speech-in-noise perception over time, these individuals were excluded from this correlation). Although the groups did not differ in overall sustained attention performance (ME group: $F(3,56) = 1.181$, $p = 0.326$), we observed a significant interaction, whereby the Catch-up group improved from year-to-year, more so than the other groups (IXN: $F(3,56) = 4.124$, $p = 0.01$; Fig. 6A). Year-to-year performance improvements were observed for the Catch-up group ($t(10) = -5.358$, $p < 0.001$) and the Low Performers ($t(16) = -2.116$, $p = 0.05$), while performance of the High Performers ($t(13) = -1.16$, $p = 0.267$) and the Reverse group ($t(18) = -2.008$, $p = 0.06$) did not change over time. The Catch-up group started off at low attention performance

levels in the first year, but eventually “caught-up” to their peers in the second year. The Catch-up group’s improvement was significantly larger than that of the High Performers ($F(22) = 11.51$, $p = 0.003$) and Low Performers ($F(25) = 6.57$, $p = 0.017$), but not the Reverse group ($F(27) = 3.08$, $p = 0.062$).

We did not observe a relationship between speech-in-noise performance from year-to-year and changes in short-term memory ($r(59) = 0.105$, $p = 0.43$), nor did we observe group differences in short-term memory in either year, or an overall difference between the years (ME group: $p > 0.05$, ME year: $p > 0.05$, IXN: $p > 0.05$).

Analysis of the speech-in-noise perception task’s trial-by-trial variability plots revealed that 7 children had level increments in the second half of the test that were greater than or equal to 2 standard deviations outside the mean ($M = +1.0$, $SD = 5.2$). Because a level increment follows an incorrect answer, we interpret large, positive numbers to signify more incorrect answers in the second half of the testing session; thus, these 7 children are thought to have exhibited a “trail-off” in their ability to attend to the task over time. Of these children, 3 were in the Reverse group, 3 were in the Low Performers group, 1 was in the Catch-up group, and 0 were in the High Performers group. Representative plots of intrinsic attention are displayed in Fig. 1.

4. Discussion

We demonstrate longitudinal relationships between speech-in-noise perception and biological and cognitive development in young children. Individual variations in speech-in-noise development correspond with the strength and development of F0 processing, but not the strength of harmonic processing. Improvement in speech-in-noise performance tracks with gains in attention, but not short-term memory or intelligence. These findings not only corroborate the previously-reported role of F0 and attention in older children and adults’ speech-in-noise perception, but for the first time extend these relationships to preschool children.

Our results demonstrate that even very young children show

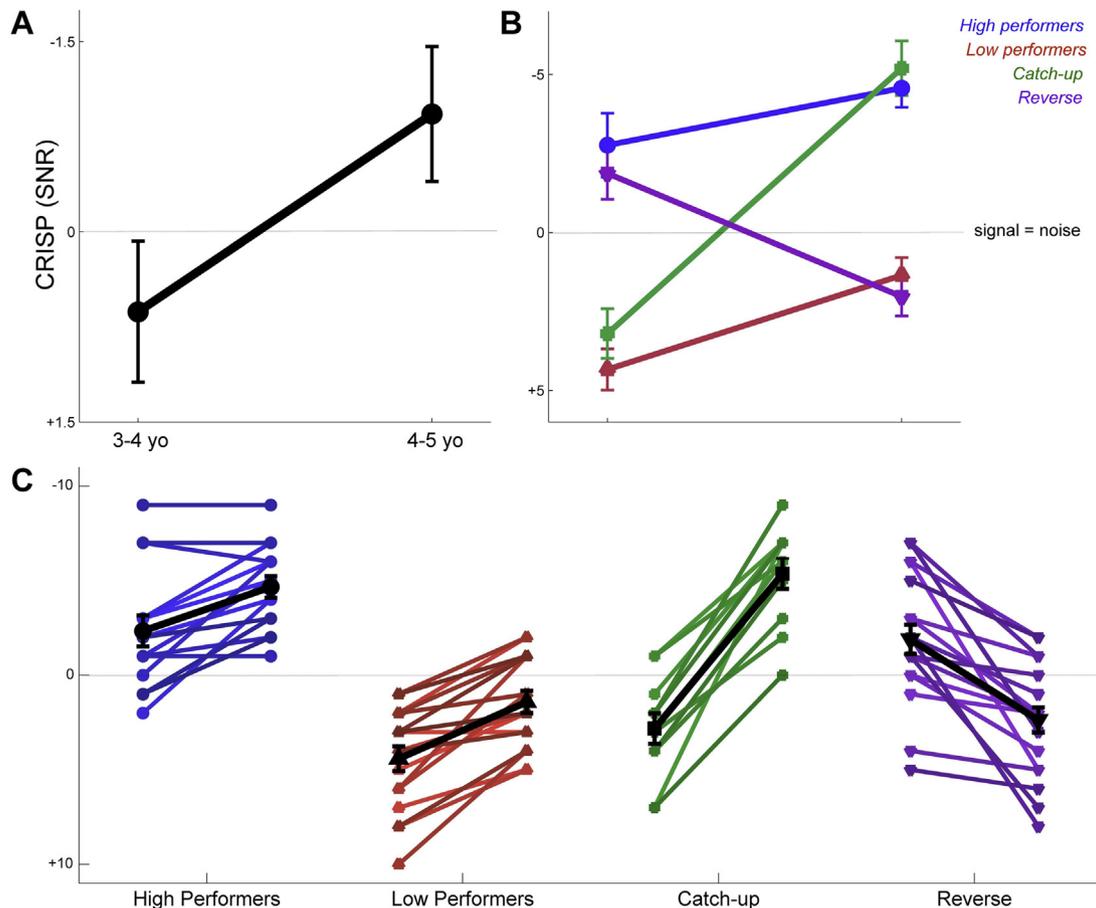


Fig. 3. [A] Performance on the CRISP, a measure of speech-in-noise perception, improves with age. [B, C] While the ability to perceive speech in noise improved for most children over the course of a year, some children's thresholds did not change, while others regressed. To characterize these variations, children were divided into four groups: High Performers (blue), Low Performers (red), Catch-Up group (green), and Reverse group (purple). Performance across years differed amongst the groups (group \times year interaction (IXN): $F(3,56) = 51.362$, $p < 0.001$). Please note reversed axis for speech-in-noise perception; better performance is plotted upwards. The line "signal = noise" represents a SNR of zero; this is the level at which the speech and noise are equal. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

improved performance as they move from preschool to kindergarten age. Previous work has highlighted key changes in speech-in-noise perception across the lifespan (Garadat and Litovsky, 2007; Kalikow and Stevens, 1977; Werner et al., 2012; Zheng et al., 2013). As the brain networks involved in sensory and cognitive functions that support hearing in noise mature rapidly in young childhood (Eisenberg et al., 2000), a number of factors could explain this finding. For instance, relative to adults, children perform poorly on complex listening tasks such as speech recognition in challenging (e.g. reverberant) listening conditions (Elliott, 1979; Nabelek and Robinson, 1982), perhaps due to heightened informational masking (Allen and Wightman, 1995; Hall et al., 2005; Oh and Lutfi, 1998), elevated levels of internal noise (Buss et al., 2006), or reduced intrinsic attention (Moore et al., 2010). Although older children are thought to be better equipped to segregate meaningful information from noise, spatial release from masking is considered "adult-like" in children as young as age three (Garadat and Litovsky, 2007; Litovsky, 2005), suggesting the auditory perceptual networks in early childhood are already developed to some extent.

In early childhood, the biological mechanisms supporting speech-in-noise perception have been undetermined. We show that variations in speech-in-noise perception are mirrored by developmental enhancements or diminutions in neural representation of the fundamental frequency (F0), an acoustic cue critical for hearing in noise. Processing of the F0 is thought to aid in

speaker identification through grouping of speech components across frequency and over time (Baumann and Belin, 2010). Additionally, making use of a target speaker's fundamental frequency is essential for successful extraction of relevant information from the auditory stream (Brown and Bacon, 2010; Carroll et al., 2003). However, the F0 is not a necessary cue for speech perception; some research has demonstrated that even with removal of low frequency speech information, and therefore the elimination of the F0, listeners are still able to achieve a pitch percept (Babel and Bulatov, 2012). Nevertheless, previous research has revealed the biological mechanisms supporting speech-in-noise perception in school-aged children and adults include F0, but not harmonics, encoding. Robust processing of F0 tracks with proficient perception of speech in noise, and a diminished processing of these spectral features is linked to difficulty perceiving speech in noise (Anderson et al., 2010; Song et al., 2011). Here we demonstrate that longitudinal (i.e., preschool to kindergarten) changes in F0 amplitude relate to changes in speech-in-noise performance, providing the first evidence that robust F0 encoding tracks with hearing in noise developmentally in young children.

The harmonic frequencies of speech, which convey timbre and formant information, are thought to augment speaker identification and localization by reinforcing the fundamental frequency via common periodicity. We did not observe a relationship between speech-in-noise perception and processing of the harmonic frequencies over time, perhaps for a few reasons. First, links between

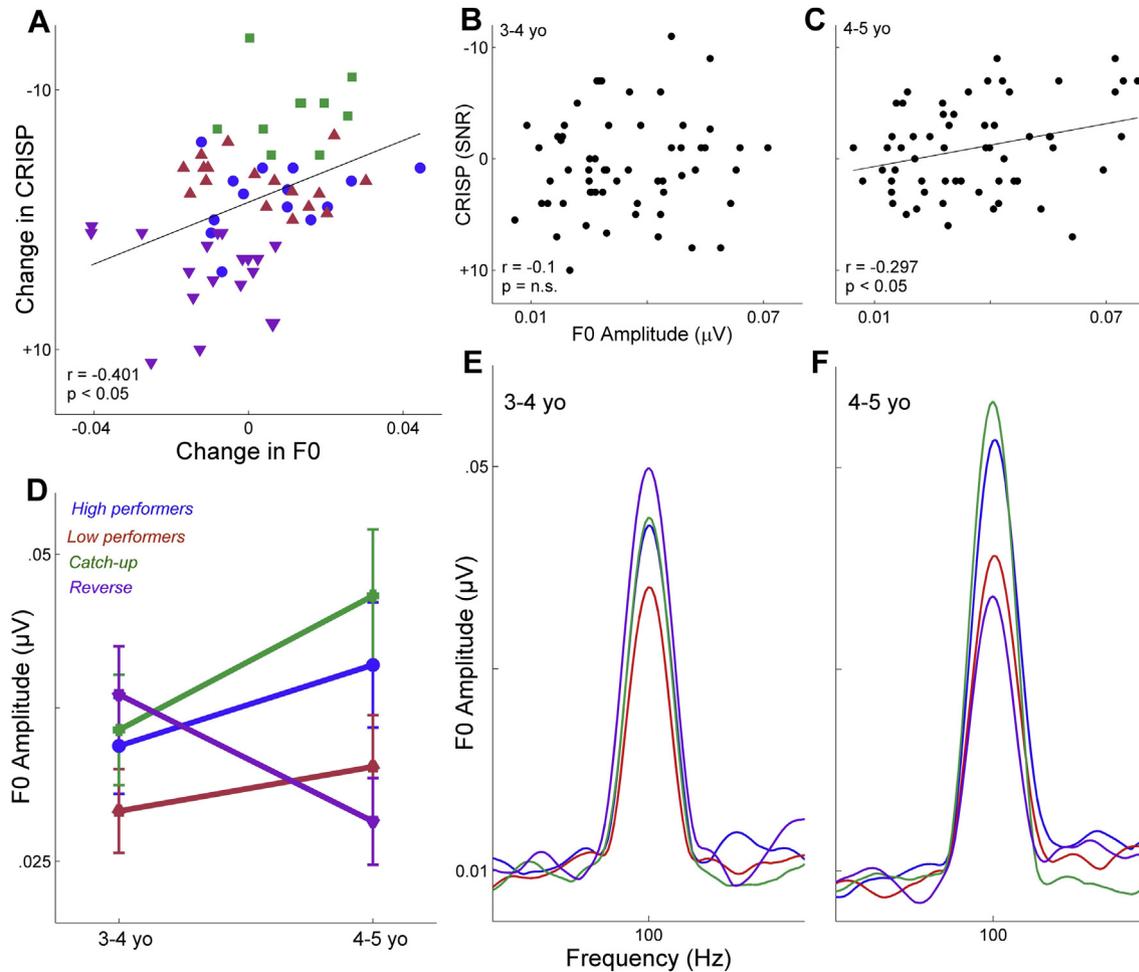


Fig. 4. Neural processing of the fundamental frequency parallels speech-in-noise development. [A] Over time, improvements and declines in speech-in-noise were associated with F0 enhancements and degradations, respectively ($r(59) = -0.402$, $p = 0.002$). [B,C] To follow-up on this correlation, we looked at relationships between hearing in noise and processing of the F0 at each time point; at age 3–4 years old, there was no significant relationship ($r(59) = -0.101$, $p = 0.448$), yet when the children were 4–5 years old, a significant relationship emerged ($r(59) = -0.299$, $p = 0.022$). [D] Among the four speech-in-noise perception groups, processing of the F0 varied, in which we saw unique year-to-year changes in F0 encoding amplitude (IXN: $F(3,56) = 6.944$, $p < 0.001$). [E, F] Response spectra of the fundamental frequency for the groups are illustrated for when the children were 3–4 years old [E] and then one year later, when they were 4–5 years old [F]. Please note reversed axis for speech-in-noise perception; better performance is plotted upwards. For these analyses, the FFR_{ENV} response spectra were used.

speech-in-noise perception and harmonics processing have been previously demonstrated in “auditory experts,” such as musicians, who have enhanced harmonic encoding relative to nonmusicians; this advantage is thought to underlie their superior speech-in-noise performance (Parbery-Clark et al., 2009; Strait and Kraus, 2013; but see Ruggles et al., 2013). In the present study, the participant population consisted of young children with little to no music training, suggesting these links may be more evident in specialized populations. Second, in contrast to the fundamental frequency, the harmonics are significantly degraded in the presence of noise. It may be the case that for young children, processing of robust cues, such as the F0, provides a more stable foundation for perception in noise. However, the role harmonics play in reinforcing the fundamental frequency periodicity in speech perception is undisputed. Previous reports have shown that in the absence of these cues, such as a loss in high-frequency encoding, perception is worsened (Anderson et al., 2013b; Buss et al., 2004; Lorenzi et al., 2006). It is important to note that in the present results, the lack of relationship does not lessen the behavioral relevance of harmonic frequencies for hearing in noise, as the stimuli and methodologies used may not have been optimal for capturing links between these speech cues and performance. Future research

should build upon this work by further investigating the importance of processing speech cues for hearing in noise in young children.

Although we do not see an overall developmental effect in the neural processing of speech cues in this early childhood group, we show associations between individual differences in auditory processing and behavioral changes in speech-in-noise perception. Until recently, the auditory brainstem was considered functionally mature by age two (Abdala and Folsom, 1995); several studies, however, point to a more prolonged developmental window of the auditory brainstem that continues into adolescence (Krizman et al., 2015; Skoe et al., 2015). The frequency following response, the metric used in this study, has been recognized for its subcortical contributions, yet recent evidence demonstrates there are cortical contributions as well (Coffey et al., 2016). These findings support the notion that the FFR is representative of different levels of auditory processing. Here, we saw that speech-in-noise perception related to processing of the F0 when the children were 4–5 years old, but not when they were 3–4 years old; this developmental window may be the tipping point in which the auditory networks that support speech processing emerge, as hearing in noise and processing of the F0 are linked in older children and adults

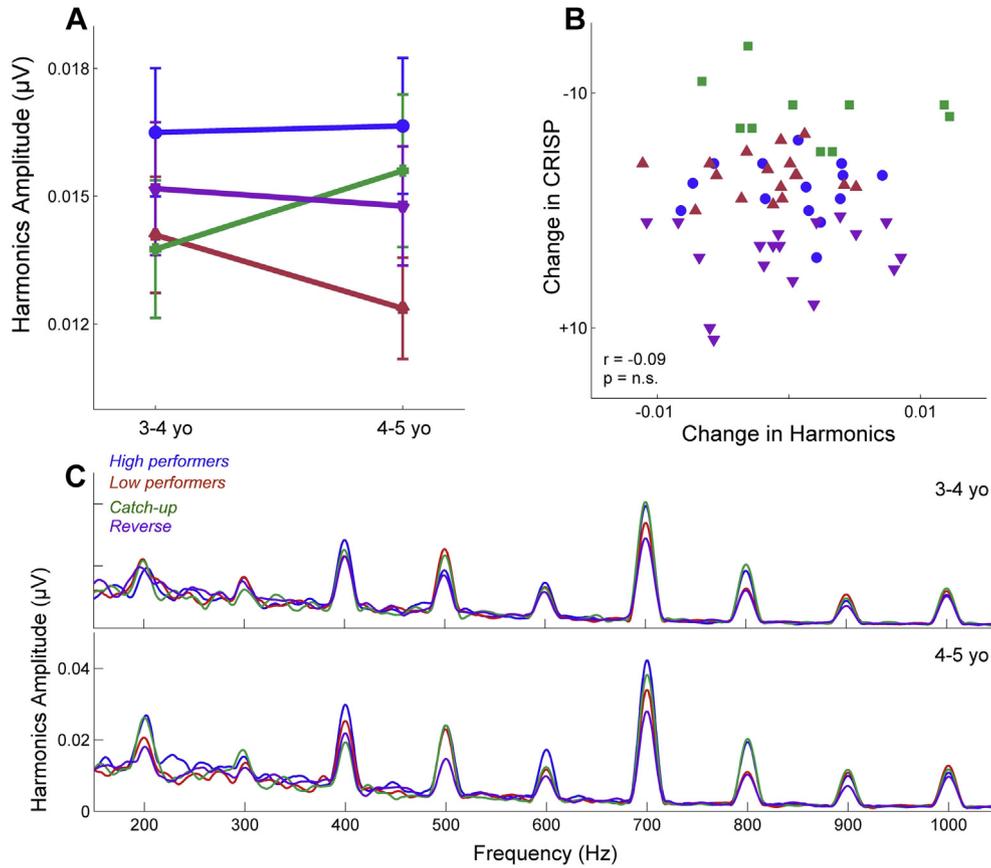


Fig. 5. Neural processing of the harmonics does not relate with speech-in-noise development. [A] The four speech-in-noise subgroups did not encode the harmonics distinctly over time (IXN: $F(3,56) = 1.05$, $p = 0.378$). [B] Changes in speech-in-noise perception were not related to processing of the harmonics over time ($r(59) = -0.091$, $p = 0.495$). [C] The response spectra of the four speech-in-noise groups. For these analyses, the FFR_{TFS} response spectra were used.

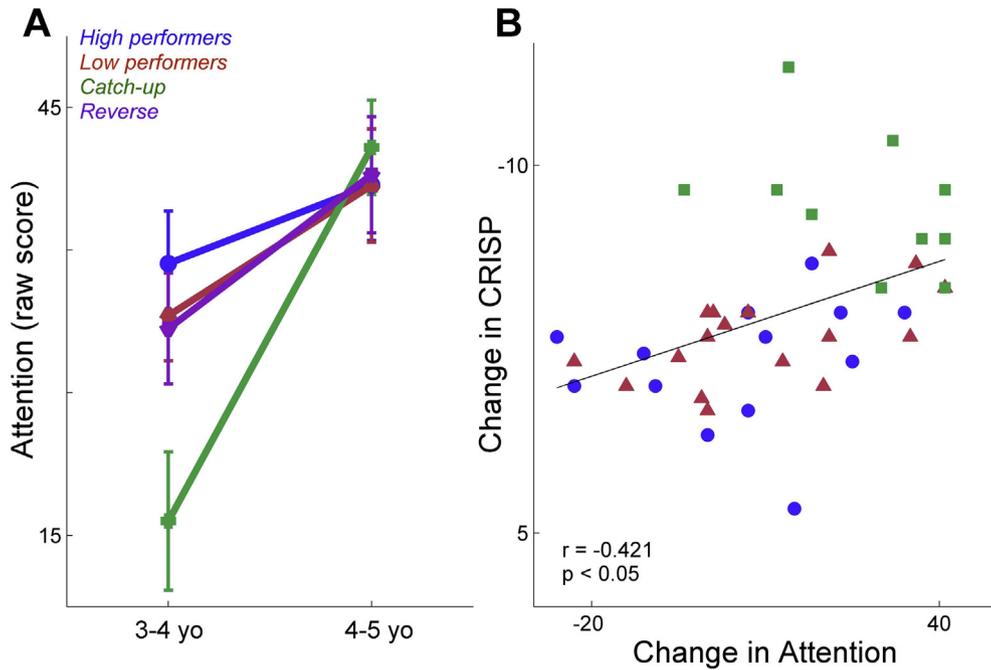


Fig. 6. [A] We observed a significant interaction, whereby the Catch-up group improved from year-to-year, more so than the other groups (IXN: $F(3,56) = 4.124$, $p = 0.01$). [B] Improvements in attention related to improvements in speech-in-noise performance ($r(38) = -0.446$, $p = 0.004$; because the Reverse group demonstrated an increase in attention despite a decrease in speech-in-noise perception over time, these individuals were excluded from this correlation.) Please note reversed axis for speech-in-noise perception; better performance is plotted upwards.

(Anderson et al., 2010; Song et al., 2011). Furthermore, it may be the case that looking at overall group patterns in auditory development obscures potential observations of unique maturational rates. Indeed, we demonstrate individual differences within a cohort of young children, in that there are different trajectories of speech-in-noise performance in young childhood. These findings are unsurprising considering the rapid rate and complexity of development in the centers that support auditory perception (Gomes et al., 2000), and we speculate that rate of maturation underlies—at least in part—these unique developmental trends. We continue to follow these children longitudinally, and future research will aim to determine exactly how individual differences in auditory development influence speech-in-noise perception.

During careful listening in a classroom (i.e. speech-in-noise perception), the process of filtering information in the perceptual stream demands attention, and age-related attention improvements augment speech-in-noise perception in school-aged children and adults (Jones et al., 2015). Here, we find the children who made the greatest improvement in their speech-in-noise perception from year to year also “caught-up” to their peers in sustained attention performance, an index of extrinsic attention. As auditory processing of spectral information is likely impacted by cognitive processes such as attention, memory, and object formation (Bauer and Bayles, 1990; Galbraith et al., 1995; Lukas, 1981), improvements in speech-in-noise perception may be driven by an interplay of top-down and bottom-up influences. Indeed, extrinsic attention to sound over time is thought to strengthen the neural networks involved in automatic processing (e.g., processing of the F0) (Kraus and White-Schwoch, 2015), and therefore, more intrinsic capabilities (e.g., intrinsic attention). The ability to attend to a signal and ignore distracters is additionally dependent on intrinsic attention, and previous reports have noted the role of intrinsic attention during auditory perceptual tasks in early childhood (Barry et al., 2010; Moore et al., 2010). Here, we analyzed the trend toward or away from improved SNR over time, and demonstrate that some children performed more poorly towards the end of the test, suggesting intrinsic attention may have waned throughout. As the majority of these plots came from poor performers (Poor Performer and Reverse groups) on the speech-in-noise task, it may be the case that reduced intrinsic attention influenced threshold estimation, leading to the classification of poor performance. Future research is needed to parse out relationships between speech-in-noise perception and extrinsic and intrinsic attention.

Although links are often drawn between memory and speech-in-noise perception (Brady et al., 1983), our results do not reveal a relationship between these skills in this cohort. One explanation for this lack of a relationship may be that short-term memory, a skill in flux in developing children, is too much of a moving target during early childhood. Alternatively, an equally likely contributing factor may be the focus of the speech-in-noise task: children were asked to identify *words* embedded in noise, a task with minimal memory demands. Absorbing a series of unconnected single words might rely on more fundamental perceptual abilities such as extracting a signal or identifying a speaker's voice, while real-world speech-in-noise perception such as conversing with a friend in a raucous lunchroom might be expected to enroll short-term memory more heavily. Indeed, rather than being asked to retrieve, remember, and repeat sentences embedded in noise, as in the case of traditional perception tasks presented to school-aged children and adults, the young children in this study were asked to listen for a male speaker within female babble, requiring speaker identification, but targeting single words. Future studies will continue to parse out relationships among auditory perception, speech-in-noise processing, and short-term memory.

4.1. Limitations

A few limitations of the present study should be addressed. First, the young age of the participants may have added additional variability to the results. For example, although the vast majority of children were compliant during the CRISP, we recognize that—as is the case with all learning evaluations—data from young children are noisy. Second, we verified peripheral hearing health with tympanometry, otoacoustic emissions, and click latencies, but not behavioral audiometry. Thus, we cannot rule out the possibility that differences in hearing thresholds have influenced the results. Previous research has demonstrated that hearing thresholds are not predictive of how an individual perceives speech in noisy environments, especially older adults (Anderson et al., 2011), but nonetheless, future investigations should rule out these relationships in young children. A third limitation is that during the electrophysiological assessment, the non-test ear was unoccluded so the child could listen to a movie. Because signals from each ear are routed to the contralateral side from early on in the auditory pathway, it is possible that masking influenced the responses during the collection. Although we cannot deny this possibility, there are reasons to believe sounds from the unoccluded ear did not affect the response. First, the movie sounds varied over the course of a recording session, and across the sample (e.g., each child selected one movie from a DVD library). Due to variation in signals over time and the law of averaging, it is unlikely that contralateral masking had more than a minimal effect on the responses, as stimulus presentation was not synced with the background soundtrack, and because the soundtrack was played at a low level (<40 dB SPL). Finally, in the event that contralateral masking did influence the response, this masking would have affected all individuals equally; each child heard a movie soundtrack during the recording session.

4.2. Clinical Implications

As noisy classrooms are challenging listening environments for young children (Bradley and Sato, 2008; Jamieson et al., 2004), those with good speech-in-noise perception stand poised to learn efficiently in classrooms, while deficiencies in speech-in-noise perception may instead limit a child's learning capacity. By and large, speech-in-noise perception improves throughout development (Elliott, 1979; Garadat and Litovsky, 2007; Litovsky, 2005; Pappo and Blood, 1989; Stuart, 2008), yet children with learning problems (e.g., auditory processing, attention and language impairments) exhibit a delayed developmental trajectory, performing more poorly than their peers (Bradlow et al., 2003; Brady et al., 1983; Moore et al., 2010; Ziegler et al., 2005, 2009). By expanding knowledge of the biological and cognitive processes supporting hearing in noise in young childhood, these findings may benefit clinicians charged with creating tailored interventions by illuminating potential factors that influence poor perception in young children.

5. Conclusions

We provide the first longitudinal evidence that speech perception in noise develops with age in preschoolers, and is linked to neural processing of the F0 and attention. Our results suggest that children may capitalize on strong auditory processing for perceiving speech in noise throughout development, and that for some children, poor attention may explain poor performance on this task. To improve speech-in-noise perception, such as that required in a classroom, it will be of benefit to determine how auditory processing and cognitive factors bolster speech-in-noise

performance, and how speech-in-noise perception in turn affects auditory processing and cognitive performance, as these two processes work in tandem but may vary within individuals.

Author contributions

All authors contributed to the interpretation of the results and the manuscript. NK contributed to study design; ECT, KWC, & SO collected and processed the data; ECT & NK analyzed the data; ECT prepared the initial draft of the manuscript; NK provided the resources and facilities.

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