The Effect of Asymmetrical Signal Degradation on Binaural Speech Recognition in Children and Adults

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To determine the effect of asymmetrical signal degradation on binaural speech recognition, 28 children and 14 adults were administered a sentence recognition task amidst multitalker babble. There were 3 listening conditions: (a) monaural, with mild degradation in 1 ear; (b) binaural, with mild degradation in both ears (symmetric degradation); and (c) binaural, with mild degradation in one ear and severe degradation in the other ear (asymmetric degradation). Sentences and babble were degraded digitally to simulate mild and severe cochlear hearing loss. All participants demonstrated significant binaural advantage (average of 7 dB) when listening to symmetrically degraded signals as compared to when listening monaurally. In contrast, adults and children achieved little or no binaural benefit, on average, when listening to asymmetrically degraded signals. Moreover, overall performance of the adults was significantly worse when listening to binaural asymmetrically degraded signals than when listening to monaural signals, thus demonstrating evidence of binaural interference. In contrast to our original speculations, however, children did not show an overall demonstration of binaural interference. Relative performance in the binaural-asymmetric and the monaural conditions was not influenced by which ear (right or left) received the more degraded signal.

KEY WORDS: binaural hearing, asymmetrical hearing loss, binaural interference, speech perception, children

The notion that two ears are better than one for listening in noisy environments has been dubbed a “psychoacoustic maxim” (Zurek, 1993, p. 255). Indeed, considerable research has demonstrated a binaural advantage for understanding speech amidst background noise (e.g., Bronkhorst & Plomp, 1988; Hawley, Litovsky, & Colburn, 1999; Licklider, 1948; MacKeith & Coles, 1971). The advantages of binaural listening include binaural summation (Scharf, 1968), improved localization ability (Humes, Allen, & Bess, 1980; Konkle & Schwartz, 1981; Newton, 1983), and binaural release from masking (Licklider, 1948).

Despite the abundance of binaural research, little is known about the ability of the auditory system to perceive speech when it is degraded asymmetrically between the two ears. It is reasonable to speculate that when the auditory system receives speech input that is degraded asymmetrically between the two ears, binaural speech perception could be poorer than if the individual were listening monaurally to the better of the two speech signals. That is, in cases where speech input is degraded

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in one ear and more degraded in the other ear (e.g., asymmetrical hearing loss), individuals may experience more difficulty perceiving speech with two ears than with the better-hearing ear alone. The term “binaural interference” has been used to describe this auditory phenomenon (Jerger, Silman, Lew, & Chmiel, 1993).

A few studies have suggested that individuals are able to derive binaural benefit when there are interaural asymmetries (Ching, Psarros, Hill, Dillon, & Incerti, 2001; McCullough & Abbas, 1992; Tyler, Parkinson, Wilson, Witt, Preece, & Noble, 2002). For example, McCullough and Abbas (1992) examined binaural syllable recognition ability in noise of 5 adults with symmetrical hearing loss who had interaural differences in speech recognition ability. Four of the 5 participants demonstrated a slight binaural advantage over the best monaural condition. In addition, some studies have demonstrated binaural advantage in individuals with cochlear implants when wearing a hearing aid on the ear opposite their cochlear implant (Ching et al., 2001; Tyler et al., 2002). These advantages were demonstrated in both adults and children on speech perception and localization tasks.

In contrast to these studies, there have been several examples in the literature of binaural disadvantage for asymmetrical signals (Arkebauer, Mencher, & McCall, 1971; Bronkhorst & Plomp, 1988; Carter, Noe, & Wilson, 2001; Chmiel, Jerger, Murphy, Pirrozzolo, & Tooley-Young, 1997; Jerger et al., 1993; Shinn-Cunningham, Schickler, Kopco, & Litovsky, 2001). Binaural disadvantage (or binaural interference) occurs when the “poorer ear” (or more degraded signal) has detrimental effects on perception by the “better ear” (or less degraded signal). It has been suggested that in some cases of bilateral sensorineural hearing loss, the two ears may be presented with disparate cochlear distortion, causing abnormal demands to be made on the auditory cortex (Hood & Prasher, 1990). For example, Arkebauer and colleagues observed that 9 of 10 participants with asymmetrical hearing loss demonstrated higher word recognition scores in the better ear under earphones than when listening with both ears in the sound field. Furthermore, 8 of the 10 participants scored higher in sound field when the poorer ear was occluded than when both ears were unoccluded. Similarly, Carter et al., Chmiel et al., and Jerger et al. reported individuals with asymmetrical speech perception abilities who demonstrated binaural interference on unaided and aided word recognition tasks, sentence identification tasks, topographical brain maps of the middle latency response (MLR), and P300 evoked potentials. Binaural disadvantage has also been shown in listeners with normal-hearing sensitivity in specific listening conditions (Bronkhorst & Plomp, 1988; Hood & Prasher, 1990; Shinn-Cunningham et al., 2001). For example, Bronkhorst and Plomp and Shinn-Cunningham et al. examined speech intelligibility in adults with normal hearing using different target signal speaker azimuths and masker speaker azimuths. The investigators found some instances where binaural performance was equal to or worse than the performance (or predicted performance) of the better ear alone. Their finding was contrary to assumptions of well-established models of binaural hearing. Hood and Prasher simulated dissimilar cochlear distortion between ears in normal-hearing listeners. Although not reaching a level of significance, binaural performance of the listeners was, on average, inferior to the better monaural score. Participants expressed that they found this binaural condition difficult and reported that they had to attend selectively to the ear with the better signal in the binaural condition.

Finally, one study has demonstrated a third category of results, “binaural indifference.” Karsten and Turner (2000) examined binaural speech discrimination ability in adults with asymmetrical hearing losses while systematically altering the balance of presentation sensation level between the two ears. Binaural performance of the listeners was not significantly better or worse than monaural performance of the better ear at any of the interaural intensity level differences.

It is possible that certain factors influence the ability to understand asymmetrically degraded speech. Two such factors are the age of the listener and which ear (right or left) receives the more degraded signal. With regard to the listener’s age, previous studies have demonstrated developmental effects on speech perception tasks that appeared to be the result of both auditory and linguistic factors. For example, Elliott, Conners, Kille, Levin, Ball, and Katz (1979) demonstrated developmental improvements in the ability to recognize monosyllabic words in quiet in children between the ages of 5 and 10 years, even though the words were well within the receptive vocabularies of 3-year-old children. Furthermore, Elliott (1979) found poorer performance on a sentence recognition task in noise in children, ages 9–13 years, than in older children and adults. Nabelek and Robinson (1982) found that 10-year-old children required higher presentation intensity levels than adults to achieve maximum performance on a speech recognition task amidst reverberation. Finally, Eisenberg, Shannon, Martinez, Wygonski, and Boothroyd (2000) examined speech recognition ability in children and adults using sentences, words, syllables, and digit spans with reduced spectral cues. Children, ages 5 to 7 years, required better spectral resolution than 10- to 12-year-old children and adults to demonstrate similar levels of performance.

In addition to age-related differences on speech perception tasks, developmental differences in auditory attention abilities have been demonstrated. Specifically, studies have demonstrated that children, particularly
young children, have difficulty differentiating and ignoring irrelevant stimuli in listening tasks compared to older children and adults (e.g., Doyle, 1973; Lane & Pearson, 1982).

In light of these age-related deficits in speech perception and selective attention skills, we hypothesized that children may have more difficulty than adults on asymmetrically degraded speech perception tasks and may more readily demonstrate binaural interference. We predicted that this age-related deficit would be most evident for younger children whose selective attention skills are not as well developed as those of older children and adults.

Left ear/right ear differences may be a second factor influencing the ability to understand asymmetrically degraded speech. It is well accepted that a majority of individuals (>90%) demonstrate left-hemisphere dominance for language (Kandell, Schwartz, & Jessel, 1991; Loring et al., 1990; Rasmussen & Milner, 1977; Woods, Dodrill, & Ojemann, 1988). In addition, numerous studies have demonstrated that most individuals show a right-ear advantage for speech stimuli on dichotic listening tasks (Breier, Hiscock, Jahrsdoerfer, & Gray, 1998; Geffen, 1976; Hiscock & Chipuer, 1993; Morris, Bakker, Satz, & Van der Vlugt, 1984). This right ear advantage for verbal input has been attributed to the right ear having privileged access to the left hemisphere. Consistent with this notion, poorer speech recognition performance, greater academic difficulty, and lower performance on verbal tasks has been demonstrated in children with right-ear unilateral hearing loss than in children with left-ear unilateral hearing loss (Bess, Tharpe, & Gibler, 1986; Jensen, Bärre, & Johansen, 1989; Jensen, Johansen & Bärre, 1989). Based on these studies, it was speculated that individuals may experience greater difficulty on a binaural task if they receive a more degraded signal in the right ear and a better signal in the left ear.

The effect of asymmetrical signal degradation on binaural speech perception can be studied quite naturally in individuals with asymmetrical hearing loss or in those with asymmetrical speech perception ability. Furthermore, investigation of this effect in these clinical populations in the future may have important implications for the fitting of amplification. However, research with these clinical populations introduces numerous extraneous variables that are rather arduous to control. These variables include, but are not limited to, speech perception ability of the better ear and the poorer ear, amount of asymmetry between the two ears, duration of deafness, duration of hearing asymmetry, and age of onset of hearing loss. For this reason, the current study examined binaural speech perception performance in children and adults with normal hearing sensitivity using stimuli that were degraded in a way that simulated the effects of cochlear hearing loss. This permitted tight control of the extraneous variables that are introduced when investigating these clinical populations.

In this study we used digital simulations of mild and severe cochlear hearing loss to examine the effect of asymmetrical signal degradation on binaural speech perception. It was expected that some listeners would experience binaural interference or, at a minimum, lose their binaural advantage for speech perception when presented with asymmetrically degraded speech signals. In addition, the current study compared the performance of children and adults to determine if the occurrence of binaural interference is contingent on the listener's age. Finally, this project investigated the influence of right ear/left ear presentation of greater signal degradation on performance.

**Method**

**Participants**

Twenty-eight children and 14 adults with normal hearing sensitivity were recruited to participate in this study. Children were divided into two groups. The younger child group consisted of 14 children (7 girls, 7 boys) between the ages of 5.0 years (months) and 6.0 (5.9). The older child group consisted of 14 children (8 girls, 6 boys) between the ages of 10.0 and 11.5 (10.5). Adults were placed in one group (9 women, 5 men) and were between the ages of 24 and 29 years (26.5). Participants had no known language, attention, or learning disabilities, and all child participants were reported by their parents to be performing at or above grade level. Finally, with the exception of 1 participant in the older child group, all participants were right-handed as demonstrated on a written task and self-report or parent report. Left-handed individuals were excluded as much as possible to reduce possible confounding factors related to hemispheric dominance for language. The 1 participant who was left-handed demonstrated performance on the experimental task that was equivalent to the rest of the older child group (i.e., within 1 SD of the older child group mean).

**Preliminary Testing**

All participants received a pure-tone audiologic assessment and demonstrated hearing thresholds of 20 dB HL or better for all audiometric test frequencies (500 Hz—4000 Hz), bilaterally. In addition, monosyllabic word recognition was tested at a level of 40 dB SL relative to the participant's speech reception threshold. Children were administered the Phonetically Balanced—Kindergarten list (PB-K; Haskins, 1949), and adults were administered the Northwestern University Auditory List
#6 (NU-6) word lists (Tillman & Carhart, 1966). All participants achieved 92% or greater on a list of 25 monosyllabic words in each ear.

The Peabody Picture Vocabulary Test—Third Edition (PPVT-III; Dunn & Dunn, 1997) was administered to all child participants to assure age-appropriate receptive vocabulary skills. The PPVT-III is a nationally standardized, individually administered measure of spoken vocabulary for children, ages 2 to 17 years, and adults. All children exhibited average or above average performance. For the group of younger children, standard scores were in the range of 103–132, with a mean score of 113.8. The range of standard scores for the group of older children was 101–143, with a mean score of 121.2. Adult participants were not administered the PPVT-III because it was assumed that their vocabulary skills were adequate for the experimental task. With the exception of 1 participant, all adults who participated in this project had at least a college degree, and the 1 participant who had not completed college demonstrated performance on the experimental task that was equivalent to the rest of the adult group (i.e., within 1 SD of the adult group’s mean).

Because the experimental task required spoken responses, and because previous research has demonstrated that children with articulation problems tend to have auditory perceptual deficits (e.g., Ohde & Sharf, 1988), the Arizona Articulation Proficiency Scale—Third Revision (AAPS-3; Fudala, 2000) was administered to all child participants to ensure age-appropriate articulation skills. The AAPS-3 is a nationally standardized picture identification test that examines children’s abilities to articulate the various phonemes of the English language. All children demonstrated age-appropriate abilities on this task. Because all of the adult participants were known by the investigator not to have articulation problems, this articulation test was administered only to the children who participated in this study.

Speech Perception Testing
Speech Materials

Sentence materials from the Hearing-in-Noise Test for Children (HINT-C; Gelnett, Sumida, Nilsson, & Soli, 1995) were used to test sentence recognition ability for both the child and adult participants. The HINT-C is composed of sentences that are readily identifiable by children (with normal hearing sensitivity) as young as 5 years of age (Gelnett et al., 1995). The sentences were derived from the original HINT sentences for adults; therefore, the sentences were not considered too easy for the adult participants.

A total of 160 of the HINT-C sentences were degraded by altering the signal digitally in the MATLAB (version 6.1; The Mathworks, Inc., 2002) programming environment. Two computer programs degraded the speech materials in a manner designed to simulate cochlear hearing loss (Moore, 1998). The audiometric thresholds listed in Table 1 were used as a basis for the mild and severe conditions.

In Step 1, the HINT-C sentences were processed first through the auditory filter-broadening program. The purpose of this program was to simulate the consequences of reduced auditory frequency selectivity, assuming impaired place coding in the cochlea. The program required entry of an upper and lower slope filter-broadening factor for 11 different frequency bands. Using the guidelines devised by Moore and Glasberg (1997) and the thresholds listed in Table 1, the broadening factors were specified for the mild and severe conditions as listed in Table 2. These broadening factors were then applied digitally to the speech materials (i.e., the HINT-C sentences). As described by Moore (1998), the computer algorithms simulated the consequences of reduced frequency selectivity by taking a short segment of the signal and calculating its spectrum via fast Fourier transform (FFT). Then the spectrum was smoothed to reduce the contrast between the peaks and valleys, and an inverse FFT was used to transform the modified signal back into the temporal domain. This process was repeated for a succession of overlapping segments and the resulting modified segments were added together (Moore, 1998).

After the HINT-C materials were processed through the auditory filter-broadening program, the resulting signals were processed in Step 2 through the loudness recruitment/threshold elevation program. Thresholds listed in Table 1 were specified as the audiometric thresholds.

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1 Dr. Brian Moore of the University of Cambridge supplied computer algorithms that served as the basis for two computer programs.

Table 1. Audiometric thresholds as a function of frequency and degradation condition.

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<th>Frequency (Hz)</th>
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Table 2. Auditory filter-broadening factor as a function of frequency and degradation condition.

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at each frequency for the mild and severe conditions. This later program simulated the effects of threshold elevation and loudness recruitment by splitting the signal into 13 frequency bands and expanding the envelope in each band before recombining the bands (Moore, 1998). The end result of Steps 1 and 2 of the processing was 160 mildly degraded HINT-C sentences and 160 of the same HINT-C sentences that were severely degraded.

Babble Noise

Digitized six-talker babble served as the competing stimuli. The spectrum of the babble was shaped to match closely the combined spectrum of the HINT-C sentences. The digitized babble then was processed through the auditory filter-broadening program and the loudness recruitment/threshold elevation program in the exact manner of the HINT-C sentences. That is, the same broadening factors and threshold parameters were used when processing the babble as those used for processing the HINT-C sentences, resulting in mildly and severely degraded babble. For the sake of this project, it was desirable that input in each experimental condition be of equal intensity regardless of the degree of degradation. Therefore, all resulting speech stimuli and babble noise were equated in terms of root mean square.

Procedures

Sentence recognition thresholds in noise were measured with insert earphones using an adaptive psychophysical procedure that tracked 50% accuracy in three experimental conditions as follows: (a) monaural—mild, in which mildly degraded sentences and babble were presented to Ear 1 only; (b) binaural—mild, in which mildly degraded sentences and babble were presented to both ears (in this condition the sentences presented to the two ears were identical, but the competing babble was uncorrelated in the two ears); and (c) binaural—asymmetric, in which mildly degraded sentences and babble were presented to Ear 1 and severely degraded sentences were presented to Ear 2. That is, the same sentences were presented to both ears, but the sentences were mildly degraded in one ear and severely degraded in the other ear. The competing babble was uncorrelated and also was mildly degraded in Ear 1 and severely degraded in Ear 2.

Ear 1 was the right ear and Ear 2 the left ear for half of the participants in each group, and Ear 1 was the left ear and Ear 2 the right ear for the other half of the participants in each group. The intensity level of the signal remained constant at 70 dB SPL and the level of the babble was adjusted adaptively. Twelve sentences were administered per run. Two adaptive runs were administered in each of the three conditions, for a total of 72 sentences. The computer selected the order of conditions. The examiner was blind to the order of conditions until all testing was completed. The order of conditions was counterbalanced across participants to minimize order effects. All three conditions were administered once before any of the conditions were repeated.

Participants were instructed to repeat each sentence. To be scored as correct, sentences had to be repeated without error. Allowable exceptions were substitutions in verb tense (is/are, have/had) and articles (a/the).

The adaptive procedure operated for the first experimental run in each condition as follows:

1. The first sentence was presented to the participant with a +4-dB signal-to-babble ratio (SBR). If the participant successfully repeated the sentence, the babble intensity level was increased by 4 dB (i.e., to a +0-dB SBR) for the second sentence. If the participant was unable to repeat the sentence correctly, the babble intensity level was decreased by 4 dB (i.e., to a +8-dB SBR) and the first sentence was repeated. The intensity level of the babble continued to decrease by 4 dB until the participant was able to repeat the first sentence successfully.

2. A ±4-dB step size was used to adjust the babble intensity level for the first five sentences. That is, if a sentence was successfully repeated, the babble intensity level was increased by 4 dB for the subsequent sentence. If a sentence was missed, the babble intensity level was decreased by 4 dB for the subsequent sentence.

3. After the first five sentences, the step size changed to ±2 dB for the remaining seven sentences in the experimental trial.

4. The interfacing computer calculated a signal-to-babble threshold (SBT) based on the average SBR of presentation for Sentences 5–13 (no 13th sentence
was presented, but the computer included the SBR that would have been presented if a 13th sentence were administered in the overall average.

The second experimental run in each condition operated like the first, except that the starting SBR for the second run was the SBT from the first run rounded to the nearest whole number plus 4 dB, and the step size was ±2 dB for the entire adaptive run.

The average of the two SBTs was calculated and taken as the final score for each participant. If the difference in SBT between the two experimental runs was greater than 5 dB in any condition, then a third experimental run, also consisting of 12 sentences, was administered in that condition. The starting SBT for the third run was the average SBT from the first two runs in that condition rounded to the nearest whole number, plus 4 dB. The step size for the third run was ±2 dB for the entire run. An average SBT from the three experimental runs was then taken as the final score for the participant.

Practice

Prior to testing, all participants listened to five sentences in quiet in the binaural mild condition. Participants were required to repeat all five sentences correctly. If one was missed, then the individual was re-instructed to repeat the sentences exactly. The participant then was administered 10 sentences in quiet binaurally and was required to repeat 9 of the 10 sentences correctly before being allowed to participate in the experimental task. Subsequent to the practice sentences presented in quiet, all participants were administered 10 practice sentences in each of the three experimental conditions using the adaptive procedure. The order of the practice runs was as follows: (a) binaural—mild, (b) monaural—mild, and (c) binaural—asymmetric. The practice runs followed similar procedures to the experimental runs, except that the adaptive runs were initiated with a +12-dB SBR, rather than a +4-dB SBR. Performance on the practice runs demonstrated to the examiner that all participants understood the instructions and were able to complete the experimental task.

Analysis

The dependent variable on the speech perception task was SBT in decibels, calculated as the average presentation SBR for Sentences 5–13 for each experimental run. As a reminder, lower SBTs indicate better performance. To determine whether there were any order effects of the experimental runs (e.g., learning effects or list effects), a repeated-measures analysis of variance (ANOVA) was conducted on the SBTs of the six experimental runs in order of presentation (i.e., Run 1, 2,...6) for each of the three age groups. Because the orders of the listening conditions were randomized across participants, this analysis allowed a test of order effects independently of condition. No significant differences were found among the six experimental runs in any of the age groups. In addition, none of the groups demonstrated significant polynomial trends in performance according to the order of the experimental runs.

For each participant, an overall score in each condition was taken as the average SBT from the two runs in each condition. If a participant required a third experimental run in a particular condition, then the overall score for that condition was taken as the average SBT from the three experimental runs. There were a total of 10 instances (out of a possible 126) in which a third experimental run was required in a particular condition—4 instances in the younger child group and 6 instances in both the older child and adult groups. None of the participants required a third experimental run in more than one condition.

Results

Mean SBTs averaged across the three listening conditions (with ranges in parentheses) were 9.98 dB (5.92–3.38 dB) for the younger child group, 5.12 dB (3.09–7.83 dB) for the older child group, and 1.59 dB (−0.21–3.48 dB) for the adult group. An ANOVA revealed significant main effects of age, $F(2, 39) = 106.98, p < .001$, and condition, $F(2, 78) = 233.91, p < .001$. Planned pairwise comparisons demonstrated that the adults significantly outperformed both the younger children, $F(1, 26) = 212.21, p < .001$, and the older children, $F(1, 26) = 37.74, p < .001$. In addition, the older children significantly outperformed the younger children, $F(1, 26) = 71.20, p < .001$.

Average scores in each condition for each of the three age groups are illustrated in Figure 1. Performance in the three listening conditions was compared by executing planned analytical comparisons in each of the three age groups (Keppel, 1991). Performance in the binaural—mild condition was superior to performance in the monaural—mild condition in the adult group, $F(1, 13) = 115.84, p < .001$; the older child group, $F(1, 13) = 176.65, p < .001$; and the younger child group, $F(1, 13) = 76.44, p < .001$. In fact, all participants showed a binaural advantage (i.e., binaural—mild performance superior to monaural—mild performance) of 1 dB or more, with the average binaural advantage being 5.79 dB for the adults, 8.05 dB for the older children, and 7.14 dB for the younger children.

The advantage of listening with two ears diminished when listening to asymmetrically degraded signals. Performance in the binaural—asymmetrical condition was significantly poorer than in the binaural—mild condition.
for the adults, $F(1, 13) = 88.63, p < .001$; older children, $F(1, 13) = 129.24, p < .001$; and younger children, $F(1, 13) = 152.41, p < .001$. All participants demonstrated poorer thresholds in the binaural–asymmetric condition than in the binaural–symmetric condition, with the average difference being 6.73 dB for the adults, 7.65 dB for the older children, and 7.42 dB for the younger children.

Comparisons of the monaural–mild and binaural–asymmetric conditions did not reveal marked differences in performance for either group of children according to ANOVA. For the adults, however, slight evidence of binaural interference was found. Average performance in the monaural–mild condition was significantly better than in the binaural–asymmetric condition for the adult group, $t(13) = 2.01, p < .05$ (one-tailed). On average, adults performed approximately 1 dB better in the monaural–mild condition than in the binaural–asymmetric condition.

Comparisons of performance between the monaural–mild and binaural–asymmetrical conditions also were examined for individual participants. Differences in individual performance between these listening conditions are shown in Figures 2, 3, and 4 for the younger child, older child, and adult groups, respectively. Notably in Figures 2 and 3, the relative performance between these two conditions was quite variable for the two groups of children. Approximately equal numbers of children showed binaural interference and binaural–asymmetrical advantage. In the adult group, however, there was a tendency for participants to demonstrate binaural interference, and this trend is apparent in Figure 4. Specifically, 11 of the 14 adults performed more poorly in the binaural–asymmetric condition than in the monaural condition, which was significant according to a sign test ($p < .05$, one-tailed).

Finally, left versus right ear comparisons were examined by dividing participants in each group into those who received the mildly degraded stimuli in their right ear and those who received the mildly degraded stimuli in the left ear. No significant differences were obtained among participants in any age group who received mild degradation in their right ear versus those who received mild degradation in the left ear when comparing the binaural–asymmetric and monaural–mild conditions. In
other words, right ear versus left ear presentation did not influence the pattern of performance in adults or children.

**Discussion**

Consistent with decades of speech perception research (e.g., Bronkhorst & Plomp, 1988; Licklider, 1948), participants in all three age groups in the current study exhibited a binaural advantage when the sentence materials were degraded symmetrically in the two ears. Comparison of performance between the monaural–mild and binaural–mild conditions revealed an average binaural advantage of 7 dB across participants in all age groups. This binaural benefit presumably is the result of two effects: (a) binaural unmasking, which has been shown in other studies that have used a diotic signal with an interaurally uncorrelated masker to yield about 1 dB improvement in intelligibility (Levitt & Rabiner, 1967; Licklider, 1948) and (b) diotic summation, which has been shown to produce about 2–3 dB improvement in speech recognition.
intelligibility for low-level speech presentation, listening in noise, and listening amidst reverberation (Davis, Haggard, & Bell, 1990; Gelfand & Hochberg, 1976; Konkle & Schwartz, 1981; Plomp & Mimpèn, 1979). Even after taking into account enhancement resulting from binaural unmasking (approximately 1 dB) and diotic summation (approximately 2–3 dB), the amount of binaural advantage observed in this study is large (7 dB).

We considered the possibility that our use of six-talker babble may have contributed to the large symmetrical advantage observed in this study, such as a masking stimulus many contribute to release from informational masking. Recent work by Arbogast, Mason, and Kidd (2002); Freyman, Helfer, McCall, and Clifton (1999); and Kidd, Mason, Rohtla, and Deliwala (1998) has demonstrated greater spatial release from informational maskers (e.g., a single talker) than energetic maskers (e.g., speech-shaped noise, Gaussian noise). Based on their research, if the babble used in this experiment produced informational masking, then we would expect a greater binaural release from masking than if we had used a purely energetic masker. However, based on findings that six-talker babble produces little, if any, additional masking compared to a random noise masker (Bronkhorst, 2000; Miller, 1947), we may conclude that informational masking was not a factor in the conditions of this study.

On average, results across age groups did not reveal that listeners performed markedly worse in the binaural–asymmetric condition than in the monaural condition. Stated differently, the poorer ear did not seem to interfere significantly with the speech recognition ability of the better ear according to the overall group data. In Figures 2, 3, and 4, participants in all three age groups showed examples of binaural advantage and binaural interference; however, adult performance was skewed toward showing binaural interference. Specifically, data from individual participants revealed that adults tended to perform more poorly in the binaural–asymmetric condition than in the monaural condition. This finding is consistent with previous reports of binaural interference (e.g., Arkebauer et al., 1971; Carter et al., 2001; Hood & Prasher, 1990; Jerger et al., 1993; Shinn-Cunningham et al., 2001). For some of the adults, the binaural interference effect was very small (i.e., less than 1 dB), but a few adults demonstrated quite substantial effects (e.g., 2–4 dB). On average, adults exhibited approximately 1 dB of binaural interference. Although a 1-dB difference seems small, a previous study using HINT materials demonstrated that a difference of 1 dB on this adaptive task corresponds to an 8.9% difference in sentence intelligibility (Nilsson, Soli, & Suminda, 1996).

Unlike the pattern with adults, the two groups of children were approximately evenly distributed between those who demonstrated a binaural advantage and those who demonstrated binaural interference. It is not entirely clear why evidence of binaural interference was prevalent in the adult group but not in the two groups of children. This finding was contrary to the original speculation that children would more readily exhibit binaural interference than would adults. It is possible that the relative lack of binaural interference in the children was related to their poor performance in the monaural condition. That is, because children generally required such a large SBR to perceive sentences in the monaural condition, adding a severely degraded signal in the opposite ear had little additional interference effect.

Although all children did not exhibit binaural interference under our laboratory conditions, it is possible that binaural interference might emerge more obviously in everyday listening environments where individuals often cannot focus exclusively on speech recognition. For example, students at school often are required to listen to the teacher while doing other things, like taking notes or following directions. In multitasking situations such as these, individuals must divide their attention between listening and a secondary task. If listening to binaural asymmetrically degraded signals requires listeners to ignore input from the poorer ear, then it is possible that performance may break down in this listening situation when effort has to be divided between listening and another task. In such real-world situations that require greater listening effort, it is possible that more children would exhibit a binaural interference effect. Consistent with this speculation, previous research suggested that children with mild–moderate sensorineural hearing impairments have more difficulty performing dual tasks that involve listening as the primary task than do children with normal hearing. Presumably this deficit is revealed because the hearing-impaired children have to expend greater effort to engage in the auditory task (Hicks & Tharpe, 2002). Future research should investigate performances of listeners in monaural and binaural asymmetrically degraded listening conditions while they are performing secondary (nonauditory) tasks.

It is possible that binaural interference was not observed for more children because of their high variability in performance, particularly in the monaural condition. Variability in group performance, as measured by standard deviation, was greater in both child groups than in the adult group for both the monaural and binaural–asymmetric conditions. In fact, variability in performance for the younger children in the monaural condition was over twice that of the adults in that same listening condition. Post hoc power analyses indicated that for both groups of children, our study had adequate power (i.e., .76) to identify a 2-dB difference between the monaural and binaural–asymmetric conditions.
However, because of the great variability in performance among the children, there was inadequate power (i.e., .45) in both age groups to identify a 1-dB difference between these two conditions. Findings from all participants suggest that a binaural-interference effect in the current project was small, on the order of 1 dB or less, which was too small to detect in the two child groups. It is possible that if larger sample sizes, different stimulus parameters (e.g., more degradation), or different speech materials (e.g., syllables, monosyllabic words) had been used, then a binaural interference effect might have been detected in the performances of the children. However, given the significant proportion of children who demonstrated a binaural-asymmetric advantage in this study, it is also possible that a significant interference effect would not be seen in larger groups of children, even under different experimental conditions.

Binaural interferences potentially may be exhibited more in terms of perceived ease and comfort of listening than in variations in speech recognition performance. Surveys of individuals with symmetrical hearing losses suggest that the use of bilateral over monaural amplification results in balanced hearing, relaxed listening, and more natural sound quality (Erdman & Sedge, 1981). However, less is known about these aspects of listening when signals are asymmetrically degraded between the two ears. Informal reports we obtained from a small sample of adult listeners with normal hearing sensitivity revealed that although they did not rate binaural-asymmetric listening as being significantly more difficult than monaural listening, several listeners complained that binaural-asymmetric listening was frustrating and annoying. These types of comments suggest that future research examining the impact of binaural asymmetry on ease of listening may be warranted.

In this study there was a clear effect of age on speech perception performance in all of the listening conditions. Adults demonstrated significantly better performance than both groups of children, and the older children clearly outperformed the younger children in all of the listening conditions. These differences were found even though there were no differences between adults and children in auditory sensitivity, as measured by pure-tone thresholds, and all participants achieved approximately 100% on monosyllabic word recognition tasks in quiet. These findings are consistent with previous research that has shown that children experience greater difficulty perceiving speech in adverse listening conditions (e.g., Eisenberg et al., 2000; Elliot, 1979; Nabelek & Robinson, 1982). This is particularly evident when sentence materials are used, because children are not as skilled as adults at capitalizing on context and the linguistic rules of speech to “fill-in” what is difficult to hear. As suggested by previous investigators, it is likely that several sensory and nonsensory factors contribute to developmental differences in speech recognition performance. These factors include growth in vocabulary, increase in frequency of word usage, increase in phonetic categories, better semantic and syntactic closure abilities, motivation, maturation in decision-making processes, and improved selective attention abilities (Boothroyd, 1970; Eisenberg et al., 2000; Elliott, 1979). Casual observation of participants’ responses in the current study suggested that knowledge or usage of the semantic and syntactic rules of language played a significant role in the poorer performance of both groups of children. It was noted that, when experiencing difficulty on the task, the children (particularly the younger children) often responded with an incomplete sentence or nonsense words, whereas adults typically responded with a sensible sentence, even if they were not sure of the correct response.

Finally, findings from the current study suggest that many individuals with asymmetrical hearing loss may not achieve binaural benefit for speech recognition. This may have implications for the fitting of binaural amplification. One must be cautious, however, when relating findings from this study to individuals with asymmetrical hearing loss. Even if the simulations used in the current project were perfect, these manipulations of the speech signal cannot account for the years of experience that one would have acquired as a listener with asymmetrical hearing loss or asymmetrical speech perception ability. Longitudinal research is needed, because both development and experience ultimately play large and important roles in amplification outcomes for children and adults. In the meantime, for individuals with asymmetrical hearing loss, clinicians should make careful recommendations regarding bilateral versus monaural amplification on a case-by-case basis.

Conclusion

Although binaural hearing is largely beneficial in most individuals when listening in background noise, findings from the current study suggest that asymmetrical signal degradation between the two ears prevents some listeners from capitalizing on the benefit of binaural speech understanding in noise. In addition to their failure to achieve binaural benefit, adults performed on average 1 dB poorer in the binaural–asymmetric condition than in the comparable monaural condition. In contrast, children did not exhibit an overall binaural-interference effect, contrary to our original speculations. On average, the children in this study demonstrated binaural indifference. That is, they produced no significant

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2This information was obtained as part of a dissertation project of the first author. Adult participants were asked to listen to sentences in the monaural and binaural–asymmetric condition, rate the ease of listening, and provide anecdotal comments.
increment or decrement in speech recognition performance when listening binaurally to asymmetrically degraded signals (relative to listening monaurally to the better of the two signals). The relative performance in the binaural–asymmetric and the monaural conditions were unrelated to which ear (right or left) received the more degraded signal.

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