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Effects of Expansion on Consonant Recognition and Consonant Audibility

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Abstract

Background—Hearing aid expansion is intended to reduce the gain for low-level noise. However, expansion can also degrade low-intensity speech. Although it has been suggested that the poorer performance with expansion is due to reduced audibility, this has not been measured directly. Furthermore, previous studies used relatively high expansion kneepoints.

Purpose—This study compared the effect of a 30 dB SPL and 50 dB SPL expansion kneepoint on consonant audibility and recognition.

Research Design—Eight consonant-vowel syllables were presented at 50, 60, and 71 dB SPL. Recordings near the tympanic membrane were made of each speech token and used to calculate the Aided Audibility Index (AAI).

Study Sample—Thirteen subjects with mild to moderate sensorineural hearing loss.

Results—Expansion with a high kneepoint resulted in reduced consonant recognition. The AAI correlated significantly with consonant recognition across all conditions and subjects.

Conclusion—If consonant recognition is the priority, audibility calculations could be used to determine an optimal expansion kneepoint for a given individual.

Keywords

Audibility; compression; expansion; hearing aids; recognition

The main goal of amplification for adults is to improve audibility while ensuring loudness tolerance. Multichannel wide-dynamic range compression (WDRC) has been used to achieve this goal. WDRC provides decreased gain as the input level is increased, in contrast to linear amplification, which provides equivalent gain up to the maximum output of the hearing aid. For high-level inputs, WDRC reduces output levels and improves loudness comfort relative to linear amplification. For low-level inputs, WDRC increases output levels and improves audibility compared to linear amplification. A common implementation is to use linear amplification for low-level inputs and compression amplification for moderate to higher-level inputs. The point at which the hearing aid switches from linear to WDRC amplification is considered the kneepoint.

Because WDRC results in increased output for low-level inputs, expansion was proposed as a method to reduce background noise (Villchur, 1973; Bray and Ghent, 2001). Expansion amplification is an opposite strategy compared to WDRC amplification and reduces gain as

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the input is decreased. When used below the kneepoint of a WDRC hearing aid, expansion amplification results in decreased output for low-level inputs. Because of the reduced output for low-level inputs, expansion can reduce unwanted hearing aid noise and background sounds.

Previous studies found conflicting results on whether subjects with sensorineural hearing loss prefer expansion amplification to linear amplification. Methodology differences could account for the discrepancies. The studies that found a preference for expansion had subjects rate expansion while using undesirable stimuli, such as low-level noise situations (Plyler et al, 2005a; Plyler et al, 2006; Lowery and Plyler, 2007; Plyler et al, 2007). The studies that found a preference for linear amplification used desirable stimuli, such as speech or music (Walker et al, 1984; van Buuren et al, 1999; Lowery and Plyler, 2007).

Regarding speech recognition, studies found reduced speech recognition with expansion when speech was presented at a low level (Walker et al, 1984; Bray and Ghent, 2001; Plyler et al, 2005a; Plyler et al, 2007). In general, when speech was presented at higher levels, equivalent recognition to that of linear amplification tended to occur (Walker et al, 1984; Preves et al, 1991; Sammeth et al, 1996; van Buuren et al, 1999; Bray and Ghent, 2001; Plyler et al, 2005a; Plyler et al, 2007). Only one study contradicts the above findings. Yanick (1976) found improved sentence recognition with expansion amplification; however, possible confounding variables were present that could have influenced the results. For example, expansion was only used in the low-frequency channel and had linear amplification above the kneepoint, whereas the comparison condition had compression above the kneepoint in both frequency bands.

It has been assumed that reduced speech recognition occurs with expansion due to reduced audibility (e.g., Walker et al, 1984; Plyler et al, 2007). However, previous studies did not measure the effect of audibility on the speech stimuli. For example, Plyler et al (2005a) measured in situ measurements of the effects of expansion on room noise and also on probe tube microphone measurements but not on the speech stimuli used in the study. Likewise, Zakis and Wise (2007) measured changes in audibility using the long-term speech spectrum as the input but did not measure changes in audibility with the specific speech tokens used in the study. Given that the long-term speech spectrum will be dominated by vowels, while recognition depends more heavily on consonant recognition, the relationship between expansion and consonant audibility needs to be better established.

Clearly an implementation of expansion that does not significantly degrade speech recognition needs to be developed. One possible way to reduce the effect of expansion is to restrict the use of expansion to low-frequency channels, as argued by Lowery and Plyler (2007). Lowery and Plyler found that restricting expansion to below 1000 Hz did not significantly affect sentence recognition. However, only using expansion below 1000 Hz defeats one of the purposes of expansion, which is to reduce internal hearing aid noise.

One factor that has not been investigated extensively is the kneepoint. The kneepoint is the input level at which the hearing aid switches between expansion amplification and WDRC amplification. In theory, increasing the kneepoint should decrease audibility because a greater portion of the speech spectrum will fall below the kneepoint. Ideally, the kneepoint should be set to a level that reduces low-level noise without affecting essential speech cues. Typical background noise has been measured at 40 to 45 dBA (Olsen, 1998). In order to reduce background noise, Plyler et al argued that the kneepoint of a single-channel hearing aid should be set to 50 dB SPL. Others argued that the kneepoint should be set to 40 dB or lower (Holube and Velde, 2000; Venema, 2005). For hearing aids with linear amplification below the kneepoint, Boothroyd et al (1994) argued that for multichannel instruments the kneepoint should be set below the long-term average speech spectrum (LTASS) in each frequency band. A similar argument could be made for setting the kneepoint of an expansion hearing aid.

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Most of the Plyler et al (2005a, 2005b) studies used a single-channel hearing aid with a kneepoint of 50 dB SPL and found decreased speech recognition. Three studies that used multichannel expansion still found reduced speech recognition (Walker et al, 1984; Plyler et al, 2007), even when the kneepoints were set at or below the LTASS for each frequency band (Plyler et al, 2007; Zakis and Wise, 2007). For this article, a 45 dB SPL LTASS will refer to kneepoints set to the LTASS in each channel for an overall speech input level of 45 dB SPL. Zakis and Wise (2007) set the kneepoints of a multichannel hearing aid to 10 dB below 45 dB SPL LTASS and 55 dB SPL LTASS. It was found that the high kneepoint level resulted in decreased speech recognition as measured by the Hearing in Noise Test, whereas the lower kneepoint did not. Because sentences were used it is difficult to assess the affect of expansion on low-level speech phonemes. When selecting a kneepoint level, it is important that the kneepoint level does not affect speech recognition for low-level phonemes that are important for speech recognition. Because existing data were collected using mostly sentence material with a higher kneepoint in some or all channels, this issue requires further investigation.

HYPOTHESES

1. Expansion with a high kneepoint will significantly reduce consonant-vowel (CV) recognition.
2. Expansion with a high kneepoint will significantly reduce CV audibility.
3. The effect of expansion on speech recognition and audibility will be reduced as the speech input level is increased.
4. There will be a positive and significant correlation between percent correct CV recognition and audibility for each condition.

METHOD

Participants

Thirteen adults aged 30 to 87 years, mean age 70 years, participated.[1] Nine of the subjects were experienced hearing aid users. The other subjects reported not wearing hearing aids. Inclusion criteria were unilateral or bilateral sensorineural hearing loss greater than 30 dB HL for at least three octave frequencies from 500 to 8000 Hz, with no threshold greater than 80 dB HL in the test ear. Figure 1 shows the mean audiogram. Audiometric and all subsequent tests, as described later, took place in a booth that met American National Standards Institute (ANSI) S3.1 (1999) standards for permissible ambient noise levels. Listeners were compensated on an hourly basis for their participation.

Individual Real-Ear-to-Dial-Differences

The Real-Ear-to-Dial-Difference (REDD) is a measurement of the difference (in dB) between the dB HL dial reading of the audiometer and dB SPL measured at the tympanic membrane of the subject. Using the REDD improves the accuracy of threshold measurements (Munro and Lazenby, 2001). In this study, the REDD was measured by inserting a probe tube into the ear canal of each subject along with the same ER3 inserts used for audiometric testing. The medial tip of the probe tube extended at least 20 mm beyond the ear canal entrance. A calibrated audiometer was used to present octave and interoctave pure tones at 70 dB HL. The output in dB SPL was recorded. The REDD was the difference in dB between the 70 dB HL and the dB SPL value, at each frequency. The REDD values were used to fit the hearing aids and calculate audibility, as described below.

[1]Power Analysis calculated for 80 percent power indicated that 12 subjects were needed.

Hearing Aid

Each subject was fit monaurally with a 15-channel commercially available digital behind-the-ear hearing aid. If the hearing loss was not symmetrical, then the ear with better thresholds was fit. If the hearing loss was symmetrical, an ear was selected at random (right ear of seven subjects, left ear of six subjects). Earmolds were acrylic canal- or skeleton-style molds with select-a-vent, medium canal length and constant-diameter #13 tubing. Vent size was 1 mm for subjects 1 and 8. The vent was plugged for subject 5 due to feedback. On the remaining subjects, the vents were 3 mm. The hearing aid was set to three different programs: (1) multichannel WDRC with an expansion kneepoint of 50 dB SPL (high kneepoint), (2) multichannel WDRC with an expansion kneepoint of 30 dB SPL (low kneepoint), and (3) linear amplification with output compression limiting (control condition).

The output for all conditions was adjusted to meet real-ear Desired Sensation Level (4.1) targets for 60 dB SPL composite speech noise and for 90 dB SPL swept pure tone (Cornelisse et al, 1995). The output for the expansion conditions was also adjusted to meet targets for 70 dB SPL composite speech noise, provided that the changes did not affect the output for 60 dB SPL. This procedure was utilized in order to ensure best fit for conversational-level speech, to equate output for conversational speech, and to avoid loudness discomfort.

The compression ratio varied across subjects, conditions, and frequency channels. Different compression ratios were used because individual real-ear targets were used and because the kneepoint was allowed to vary across conditions while keeping the output for 60 dB SPL and 90 dB SPL the same. The mean multichannel compression ratio, as indicated by the fitting software, was 1.6 (range: 1.2–2.1) and 1.9 (range: 1.1–2.7) for the low and high kneepoint conditions, respectively. Previous research has found that differences between compression ratios in that range have a negligible effect on speech recognition (Boike and Souza, 2000; Davies-Venn and Souza, 2008).

In regard to setting other hearing aid parameters, it was attempted to use clinically relevant settings. For example, hearing aids have expansion ratios that vary from 0.5:1 to 0.9:1. For this study, an expansion ratio of 0.7:1 was used, which represents the mean of expansion ratios available. Previous studies have established the fact that increasing the expansion time constant will increase the effect of expansion on speech recognition (Plyler et al, 2005b). To minimize the effect of the expansion time constant, a short expansion time constant of 200 msec, as measured using the ANSI S3.22 (1996) procedure for measuring time constants, was used. To minimize confounding variables, directional microphones, noise reduction, and feedback control were turned off.

All real-ear measurements were done with a Fonix 6500 CX. For all probe tube microphone measurements, the tube was placed 20 mm beyond the entrance to the ear canal of each subject. For the average adult ear canal size of 24 mm, the microphone should be placed within 4 mm of the tympanic membrane to minimize the effect of standing waves (Dirks and Kincaid, 1987).

Stimuli

Four voiced consonant-vowel nonsense syllables (/ði/, /vi/, /zi/, /ʒi/) and four unvoiced CV syllables (/θi/, /fi/, /si/, /ʃi/) from the Nonsense Syllable Test (NST [Dubno and Dirks, 1982]) were presented to the subjects. These consonants were selected because (1) they include a range of low to medium consonant levels likely to be affected by expansion and (2) previous research has found many of them to be easily confusable (Stelmachowicz et al, 2001; Steeneken and Houtgast, 2002). The stimuli were up-converted from a sampling rate of 33 to 48 kHz for equipment compatibility. The stimuli were routed from a PC to a digital-to-analog converter

(Tucker Davis RX6) to a pair of attenuators (Tucker Davis PA5) to a speaker. The subject sat 1 m at 0 degrees azimuth from the speaker. The stimuli were presented at 50, 60, and 71 dB SPL in quiet for each hearing aid condition. The speech presentation levels were chosen to represent a range of soft to loud conversational speech levels (Dunn and White, 1940; French and Steinberg, 1947; Cox et al, 1988; Denes and Pinson, 1993; Olsen, 1998). The presentation level was calibrated at the position of the subject's head to the root mean square pressure of the calibration tone provided with the NST.

The subject was familiarized with the stimuli by listening to each CV syllable at 60 dB SPL with the hearing aid set to the linear condition. Next the subject completed a practice trial that consisted of an eight-alternative forced-choice paradigm with reinforcement. Each stimulus was presented in random order for a total of eight presentations (one each). Afterward the subject again listened to each CV syllable and then completed another practice trial with reinforcement. This process continued until the subject's performance plateaued. Final data collection consisted of an eight-alternative forced-choice paradigm without reinforcement. Each CV syllable was presented 10 times for each condition, giving a total of 80 randomly ordered syllables per condition. To ensure activation of expansion prior to each stimulus presentation, the minimum duration between presentations was one second. The order of test conditions was randomized. The subject selected the response from eight alternatives via a touch screen. All presentations and responses were controlled with a MATLAB (MathWorks) computer program created by the first author.

Recordings of aided stimuli were made at the tympanic membrane for each subject (Souza and Tremblay, 2006). A probe tube was inserted 20 mm beyond the ear canal entrance. The probe microphone (Etymotic ER7) was connected to a Tucker Davis RX6 for analog-to-digital conversion at 48,828 Hz. A one-second pause was used between presentations. The recordings were saved to a computer for off-line analysis.

AIDED AUDIBILITY INDEX

Signal audibility was quantified using the Aided Audibility Index (AAI [Stelmachowicz et al, 1994]) with the modifications suggested by Souza and Turner (1998). This measure is similar to the Speech Intelligibility Index (ANSI, 1997) but also encompasses amplification parameters including the maximum output and compression ratio. Subject audiograms were converted to dB SPL at the tympanic membrane using individually measured REDD values. To increase precision, thresholds were converted into third-octave-centered frequencies from 160 to 8000 Hz using the formula described by Pittman and Stelmachowicz (2000). The individual speech tokens were concatenated for each subject and condition and used to measure dB SPL levels, as follows. Using MATLAB (Math-Works) and a computer program written by Couvreur (1997), the peak and bottom 10 percent SPLs were measured for each third-octave band of the concatenated stimuli, using a short nonoverlapping time window of 100 msec to measure short-term variations in the level. For nonlinear amplification, the speech dynamic range used in the AAI calculation must be adjusted to account for amplitude compression. Souza and Turner (1999) showed that using the actual speech dynamic range in place of the assumed dynamic range could improve AAI predictive value. Accordingly, the speech dynamic range was calculated by subtracting the average peak SPL across each frequency from the average bottom SPL across each frequency for each amplification condition, speech input level, and subject. The AAI was calculated by comparing the peak SPL in each band to the subject threshold for that band. Each band was weighted using the NST band importance functions from ANSI (1997) standards for the calculation of the Speech Intelligibility Index and then summed across bands and divided by the speech dynamic range. This resulted in an AAI number between 0 and 1 for each condition and subject, with 1 representing maximum audibility.

RESULTS

Effect on Consonant Audibility

The amplified CV SPLs for subject 11 at 50 and 71 dB SPL are plotted in Figure 2. When expansion with a high kneepoint was used, audibility was reduced when speech was presented at 50 dB SPL. Similar findings were noted for the other subjects and CV stimuli.

The AAI by condition and speech input level is plotted in Figure 3. When expansion with a high kneepoint was active, audibility was reduced across all input levels. To see if the AAI varied with the expansion condition, a two-way repeated-measures analysis of variance (ANOVA) was conducted. The AAI at each presentation level for the two expansion conditions was subtracted from the control condition (linear amplification) for each subject to create the dependent variable. The independent variables were the expansion minus linear amplification conditions (low kneepoint, high kneepoint) and speech presentation level (50 dB SPL, 60 dB SPL, 71 dB SPL). There was significant interaction between the condition and the speech intensity level ($F[2, 24] = 5.21$, $p < .05$). Because of the significant interaction paired-sample *t*-tests were completed at each speech intensity level. The error rate was controlled using the Bonferroni procedure. Results indicated a significant difference in the AAI between the expansion conditions at all of the speech input levels ($p < .05$). In summary, expansion with a high kneepoint significantly reduced audibility at all input levels when compared to expansion with a low kneepoint.

Effects on Consonant Recognition

Consonant-vowel recognition scores were averaged across participants for each condition and speech input level, which are presented in Figure 4. The percent correct for the high kneepoint expansion condition was lower, especially at 50 dB SPL and 60 dB SPL, compared to the other two conditions. The CV recognition scores for the high kneepoint expansion condition and the low kneepoint expansion condition were subtracted from the linear (control) condition. To determine if consonant recognition was determined by the expansion condition or speech input level, a two-way repeated-measures ANOVA was conducted. The dependent variable was CV difference score (expansion – control). The independent variables were expansion condition (low kneepoint, high kneepoint) and speech intensity level (50 dB SPL, 60 dB SPL, 71 dB SPL). The analysis reveals that the interaction was not significant ($F[2, 24] = 2.99$, $p = .07$). There were significant main effects for the expansion condition ($F[1, 12] = 67.69$, $p < .05$), with poorer scores for the high kneepoint condition. There was not a significant effect for the speech intensity level ($F[2, 24] = 0.57$, $p < .57$). These results indicated that there was a significant difference in recognition scores between the expansion conditions, but this difference did not vary significantly across input levels.

Effect of Audibility on Consonant Recognition

Figure 5 is a scatter plot of the CV percent correct versus AAI for each condition. As the AAI increased, CV recognition scores improved. A linear regression model was fit to evaluate whether consonant recognition scores were significantly associated with audibility. The independent variable was the AAI, and the dependent variable was the CV recognition score. Regression analysis indicates that the CV recognition scores were significantly associated with audibility as measured by the AAI ($F[1, 115] = 61.57$, $p < .05$). The regression slope was 0.48; therefore, for each 10 percent increase in AAI, the mean CV proportion score was expected to increase by 4.8 percent.

DISCUSSION

The results confirmed the first hypothesis: CV recognition decreased significantly for the high expansion kneepoint condition. These findings are consistent with previous studies that found reduced speech recognition with high kneepoints in all or some of the frequency channels (Walker et al, 1984; Plyler et al, 2005a, 2005b; Lowery and Plyler, 2007; Plyler et al, 2007; Zakis and Wise, 2007). This was the first study to have used low-level kneepoints in all frequency channels. One other study varied the kneepoint level used. In that study sentence recognition thresholds equivalent to those of linear amplification below the kneepoint occurred once the kneepoint was reduced to 45 dB SPL in the single-channel condition or to 10 dB below the 45 dB SPL LTASS in each frequency band for the multiple-channel condition (Zakis and Wise, 2007). Because sentences were used, the effects of expansion were likely mitigated compared to the CV stimuli used in this study.

The second hypothesis, that expansion with a high kneepoint would significantly reduce audibility, was confirmed in the results. The implications for the reduced audibility will be explored in detail after proceeding with a discussion on the third hypothesis. The third hypothesis, that the effect of expansion on CV recognition and audibility would decrease as the input level was increased, was not supported by the data. Instead CV recognition and audibility were significantly reduced at all input levels. This result was unexpected given that previous studies that used multiple speech input levels found that expansion did not affect speech recognition above a certain input level (Walker et al, 1984; Bray and Ghent, 2001; Plyler et al, 2005a; Plyler et al, 2007). The different speech presentation levels, speech material, and hearing aid settings used could explain the discrepant results. For example, the speech input level for this study only went up to 71 dB SPL, whereas Walker et al (1984) used presentation levels as high as 80 dB SPL. Similarly, sentences instead of CV stimuli were used in the Plyler et al studies. The longer duration of sentences meant that expansion was probably deactivated for a greater portion of the speech compared to the CV stimuli used in this study. Furthermore the stimuli used for this study were chosen because they had low to medium consonant levels, making them more likely to be affected by expansion.

In addition to the different speech presentation levels and speech material, different hearing aid settings across studies could account for the discrepant results. The expansion time constant is the amount of time that it takes the hearing aid to switch into or out of expansion. Plyler et al (2005b) established that increased expansion time constants could result in reduced sentence recognition. This study used a time constant of 200 msec, whereas other studies using multiple speech input levels used expansion time constants as short as 3 msec to as long as 512 msec (Walker et al, 1984; Plyler et al, 2005a; Plyler et al, 2007). Bray and Ghent (2001) did not specify the expansion time constant used.

The expansion ratio is another hearing aid setting that could account for the incongruent results. The expansion ratio is the change in hearing aid input divided by the change in hearing aid output. Lower-level sounds should be amplified less as the expansion ratio is decreased, thus reducing audibility. No study to date has established the effect of the expansion ratio on speech recognition or audibility. Not all of the previous studies reported the expansion ratio, but this study used an expansion ratio of 0.7:1, and Plyler et al (2005a; Plyler et al, 2007) used 0.5:1. It is also not known if changing the expansion ratio by 0.2 results in significant changes in audibility or speech recognition.

In summary, use of different stimuli and hearing aid settings across studies makes it difficult to directly compare results. However, a consensus across studies can be seen. Expansion with a high kneepoint results in decreased speech recognition.

Expansion had been assumed to cause reduced audibility of speech in previous studies. It was postulated that the reduced audibility caused reduced speech recognition. However, audibility of the speech stimuli used in previous studies was not directly measured, and therefore the claim that reduced audibility caused reduced speech recognition could not be verified. In the present study, audibility calculated using the AAI was significantly lower for the high kneepoint expansion condition relative to the low kneepoint expansion condition at all speech input levels.

To assess the position that the reduction in audibility was correlated with a reduction in speech recognition, a regression analysis was completed. Consistent with the fourth hypotheses, results indicate that the AAI was a significant predictor of CV recognition scores. There was significant variability in the data, as indicated in Figure 5. R^2 is a measure of the variability that was explained by the model. R^2 in the regression analysis was 0.34 (maximum 1), indicating that the regression model proportionally accounted for 34 percent of the variability. Previous studies found a wide range in performance as a function of audibility (Dubno and Dirks, 1989;Souza and Turner, 1999). In summary, the regression analysis indicates a significant correlation between audibility and CV recognition but that, as is typical for speech recognition, audibility did not explain all of the variability.

Temporal cue modifications from expansion may account for additional variability. Since expansion changes the amount of amplification that occurs over time, it is expected to affect temporal cues. Time waveform plots were created in order to gain an understanding of the temporal effects of expansion. Figure 6 shows a plot of /si/ at 50 dB SPL and 71 dB SPL for subject 10 under each amplification condition. At 50 dB SPL for the high kneepoint condition both the consonant and vowel portions were reduced in amplitude compared to the linear and the low kneepoint condition. Minimal differences were noticed when comparing the linear with the low kneepoint condition. At 71 dB SPL a different effect from expansion was observed. The consonant portion was reduced, whereas the vowel portion was preserved in amplitude. The consonant-to-vowel intensity difference is important for consonant recognition (Walker et al, 1984;Hedrick and Younger, 2007). By altering the consonant-to-vowel intensity difference it is possible that expansion degraded temporal cues, thereby affecting speech recognition.

Under certain conditions, WDRC alters temporal cues (particularly the amplitude envelope), causing degraded speech recognition (Souza and Turner, 1998; Souza, 2000; Souza and Kitch, 2001). The use of WDRC in the study design made it difficult to distinguish the temporal effects of expansion from the temporal effects of WDRC on the stimuli. It is important that future studies establish the relationship between expansion and its effect on temporal cues.

CLINICAL IMPLICATIONS

Two reasons to use expansion are (1) to reduce internal hearing aid noise and (2) to reduce background noise. Internal hearing aid noise is 20 to 25 dB SPL (Holube and Velde, 2000; Kuk, 2002), and background noise has been measured at 40 to 45 dBA (Olsen, 1998). A consequence of using a high kneepoint is reduced speech recognition. In order to reduce the negative effect of expansion, using a low kneepoint is preferable. A kneepoint of 30 dB SPL across all frequency channels is sufficient for reducing internal hearing aid noise but will also preserve speech audibility.

This study did not evaluate the effect of kneepoints in between 30 and 50 dB SPL. Therefore it might be possible to use a higher kneepoint in some or all of the frequency channels without affecting speech recognition or audibility. We also argue that, in order to minimize the effects of expansion on the audibility of low-level consonant sounds, a kneepoint lower than those deemed acceptable for longer-length speech material (e.g., Zakis and Wise, 2007) should be used. Based on this argument, the kneepoint should be set to 30 dB SPL unless future studies find that using a higher kneepoint does not significantly affect recognition.

We have argued that low expansion kneepoints will optimize consonant audibility. One caveat is that the present study did not evaluate subjective preferences for expansion. If a hearing aid is optimized for audibility, then the patient may not wear the hearing aid because of excessive background noise. Because background noise has been measured at 40 to 45 dBA (Olsen, 1998), it is unlikely that using a kneepoint of 30 dB SPL is sufficient for reducing background noise. That is, current implementations of expansion cannot distinguish between low-level speech and low-level noise. A better alternative might be to use active noise reduction for low-level inputs. Active noise reduction can reduce background noise while maintaining speech recognition (Ricketts and Hornsby, 2005). Current hearing aids do not utilize active noise reduction for low-level inputs, but this could be implemented. Recent studies have found that subjects prefer active noise reduction (Boymans and Dreschler, 2000; Ricketts and Hornsby, 2005). No study to date has evaluated subjective preferences for active noise reduction versus expansion.

CONCLUSION

Expansion amplification with a high kneepoint reduced consonant recognition and CV audibility when compared to expansion amplification with a low kneepoint. CV recognition and audibility were found to correlate significantly, but audibility did not account for all of the variability. To avoid degrading speech audibility it is recommended that expansion be used with a low kneepoint. Future research should include kneepoint levels between 30 and 50 dB SPL and should investigate the relationship between expansion and other acoustic distortions such as temporal cue modifications. Future research should also investigate the subjective preferences of expansion versus active noise reduction.

Abbreviations

AAI, Aided Audibility Index; CV, consonant-vowel; LTASS, long-term average speech spectrum; NST, Nonsense Syllable Test; REDD, Real-Ear-to-Dial-Difference; WDRC, wide-dynamic range compression.

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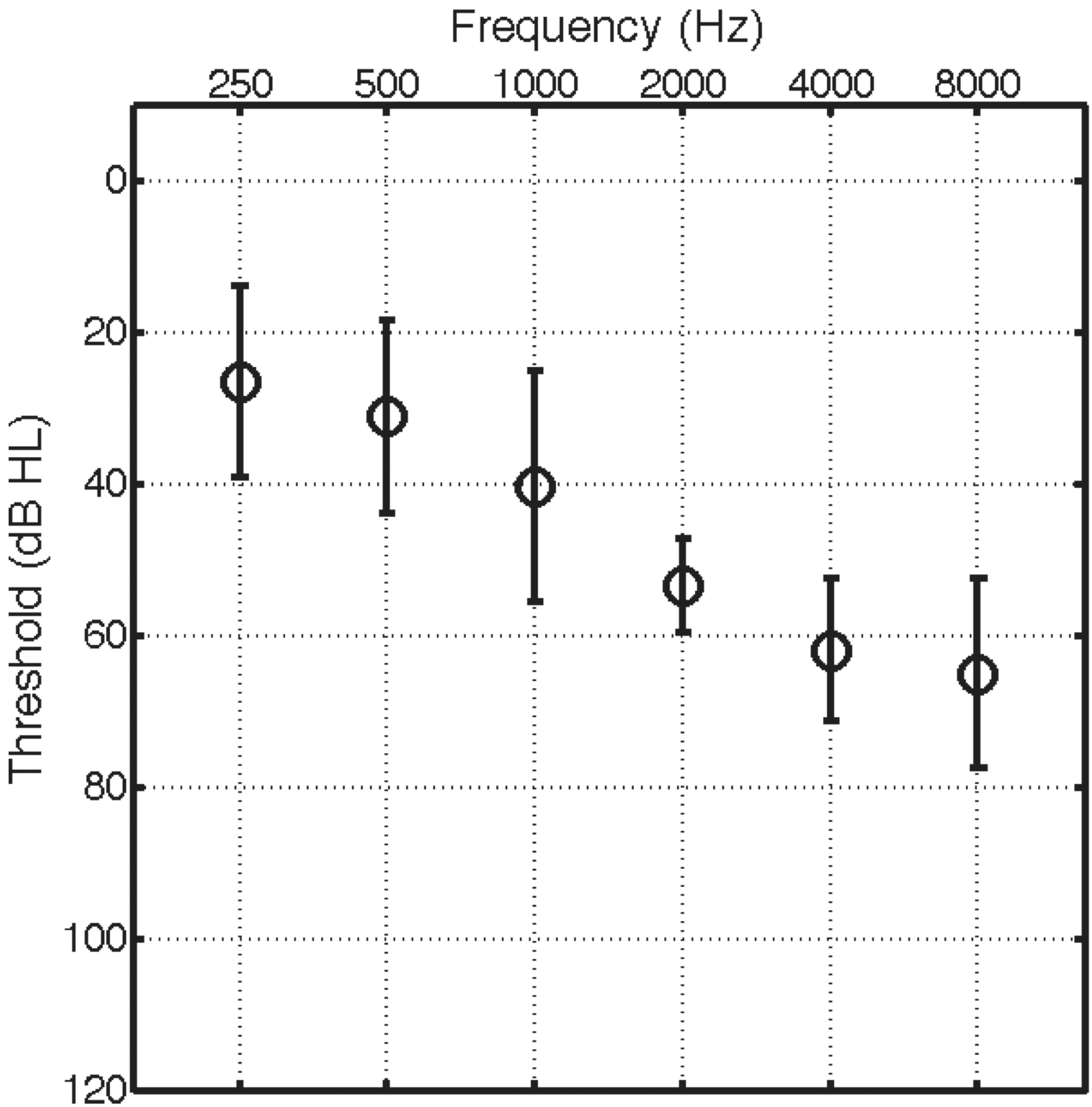

Figure 1.
Mean test ear air conduction thresholds. Error bars represent ± 1 standard deviation.

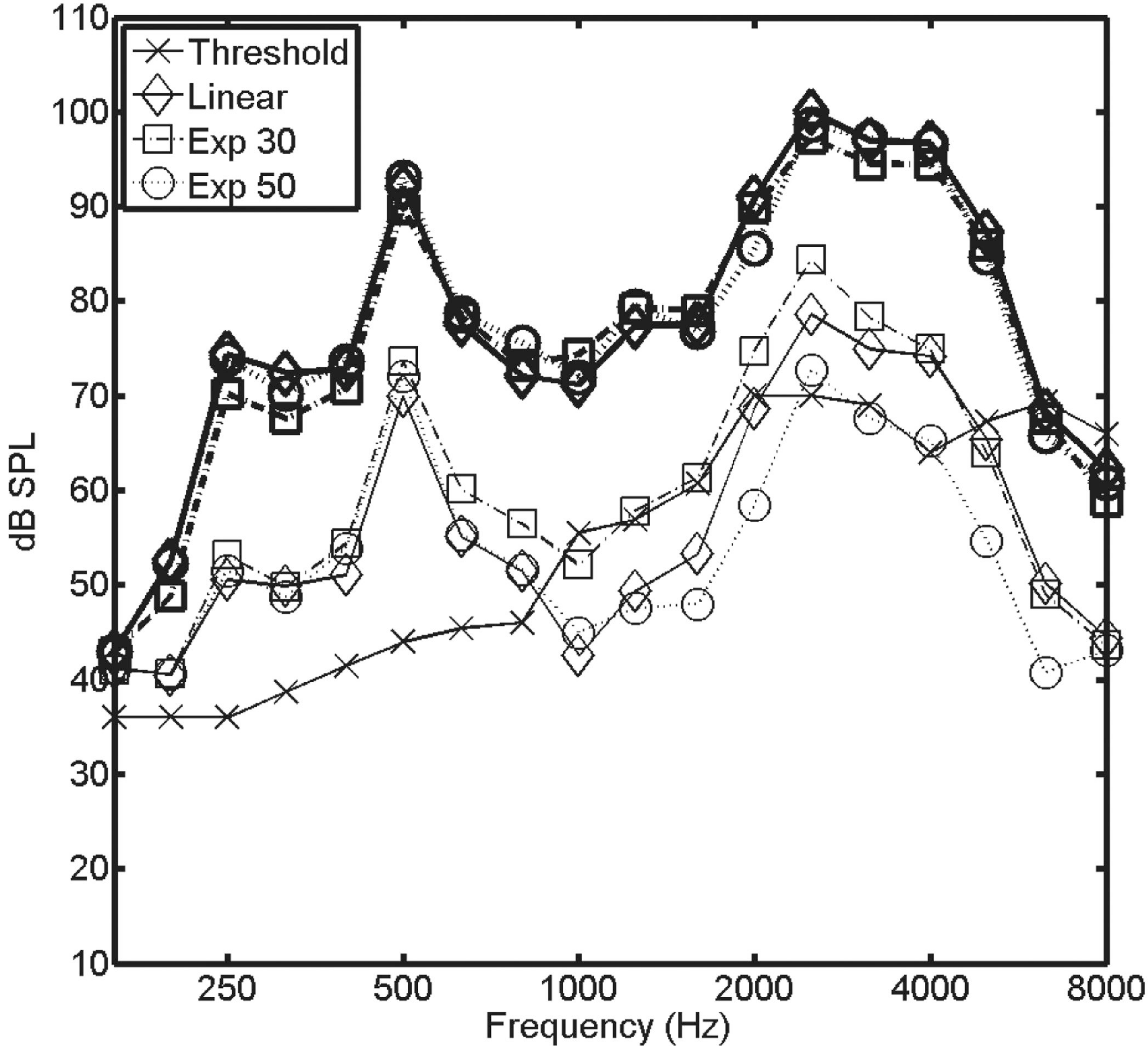

Figure 2.
Plot of RMS SPL of /θi/ for subject 11 by hearing aid condition. Thin lines represent 50 dB SPL CV input level and thick lines represent 71 dB SPL CV input level. Portions above threshold are audible.

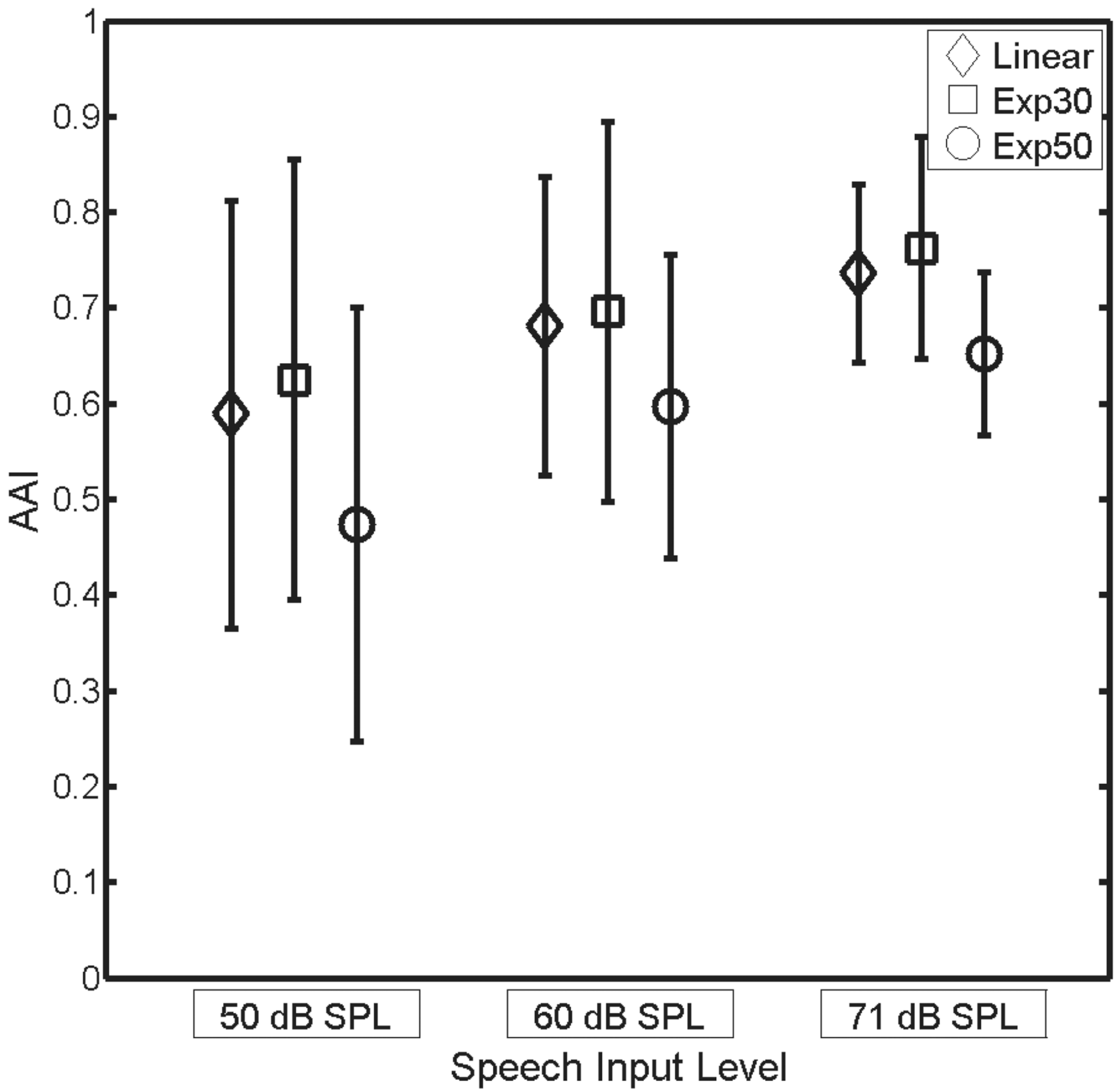

Figure 3.
Mean AAI by condition and input level. Error bars represent ± 1 standard deviation. Lin = Linear; Exp30 = Expansion with 30 dB SPL kneepoint; Exp50 = Expansion with 50 dB SPL kneepoint.

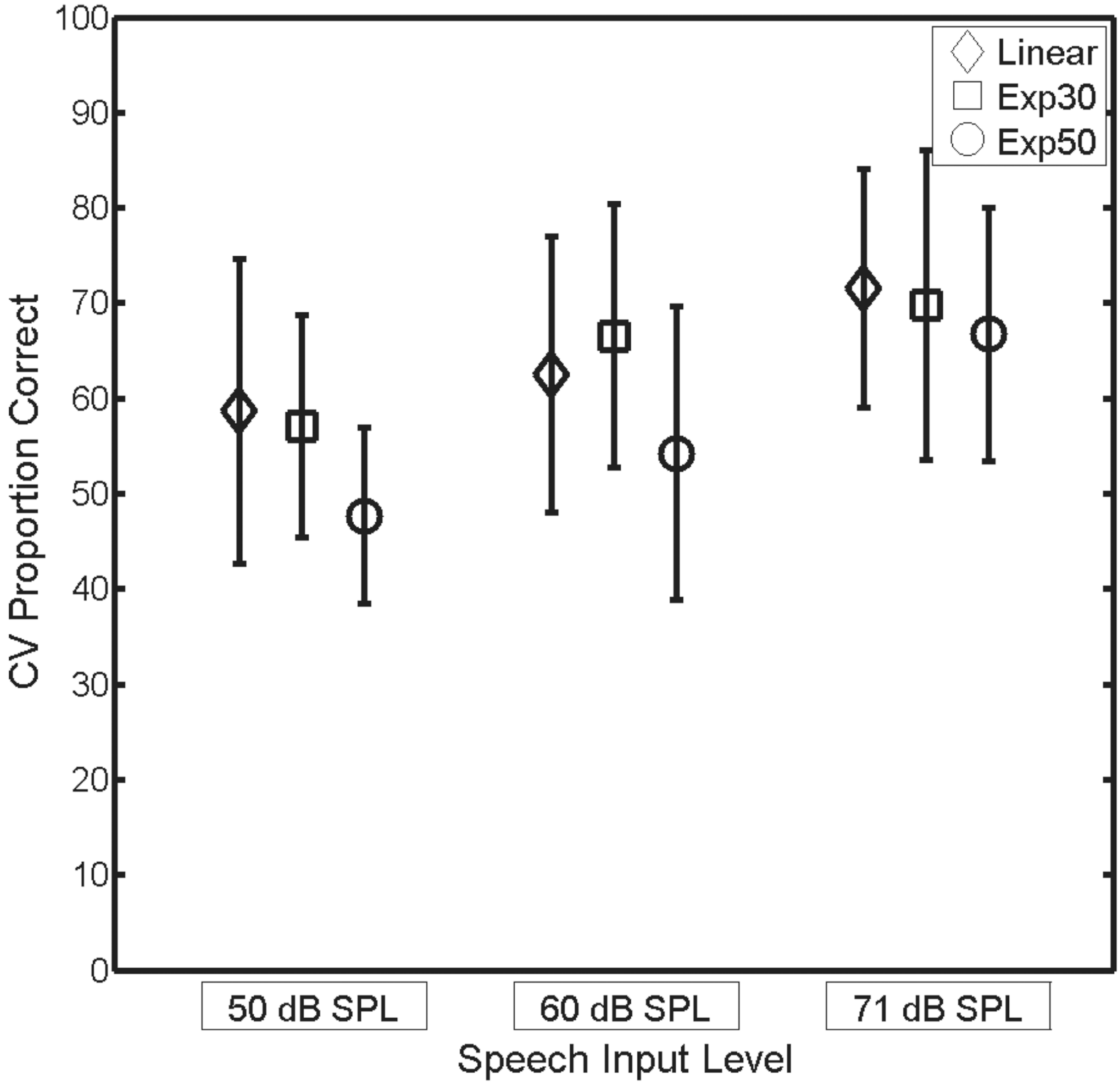

Figure 4.
Mean CV percent correct by condition and input level. Error bars represent ± 1 standard deviation. Lin = Linear; Exp30 = Expansion with 30 dB SPL kneepoint; Exp50 = Expansion with 50 dB SPL kneepoint.

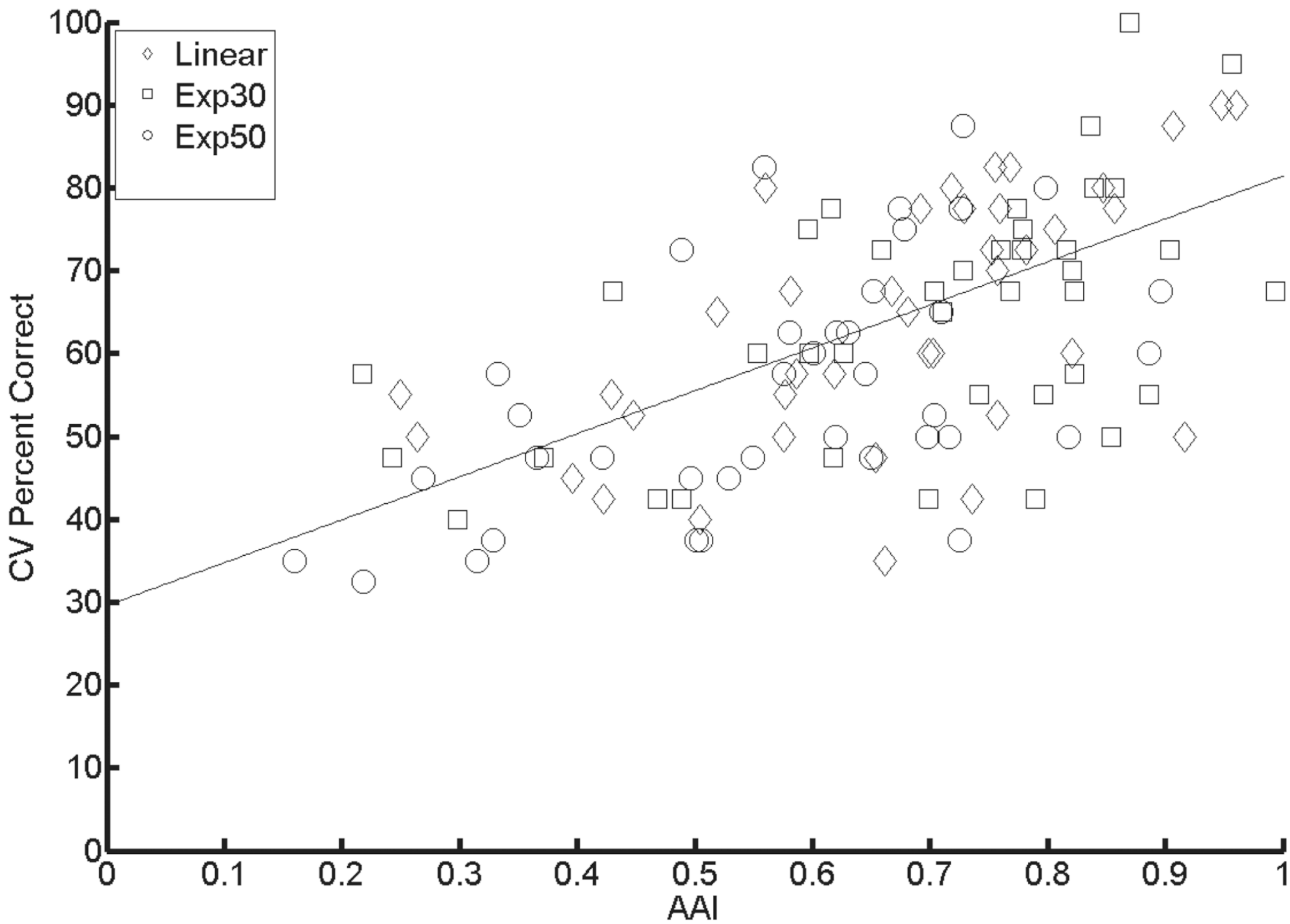

Figure 5.

Scatterplot of CV percent correct versus AAI for each condition, speech input level, and subject. Solid line is the fitted linear regression equation for all the conditions. Lin = Linear; Exp30 = Expansion with 30 dB SPL kneepoint; Exp50 = Expansion with 50 dB SPL kneepoint.

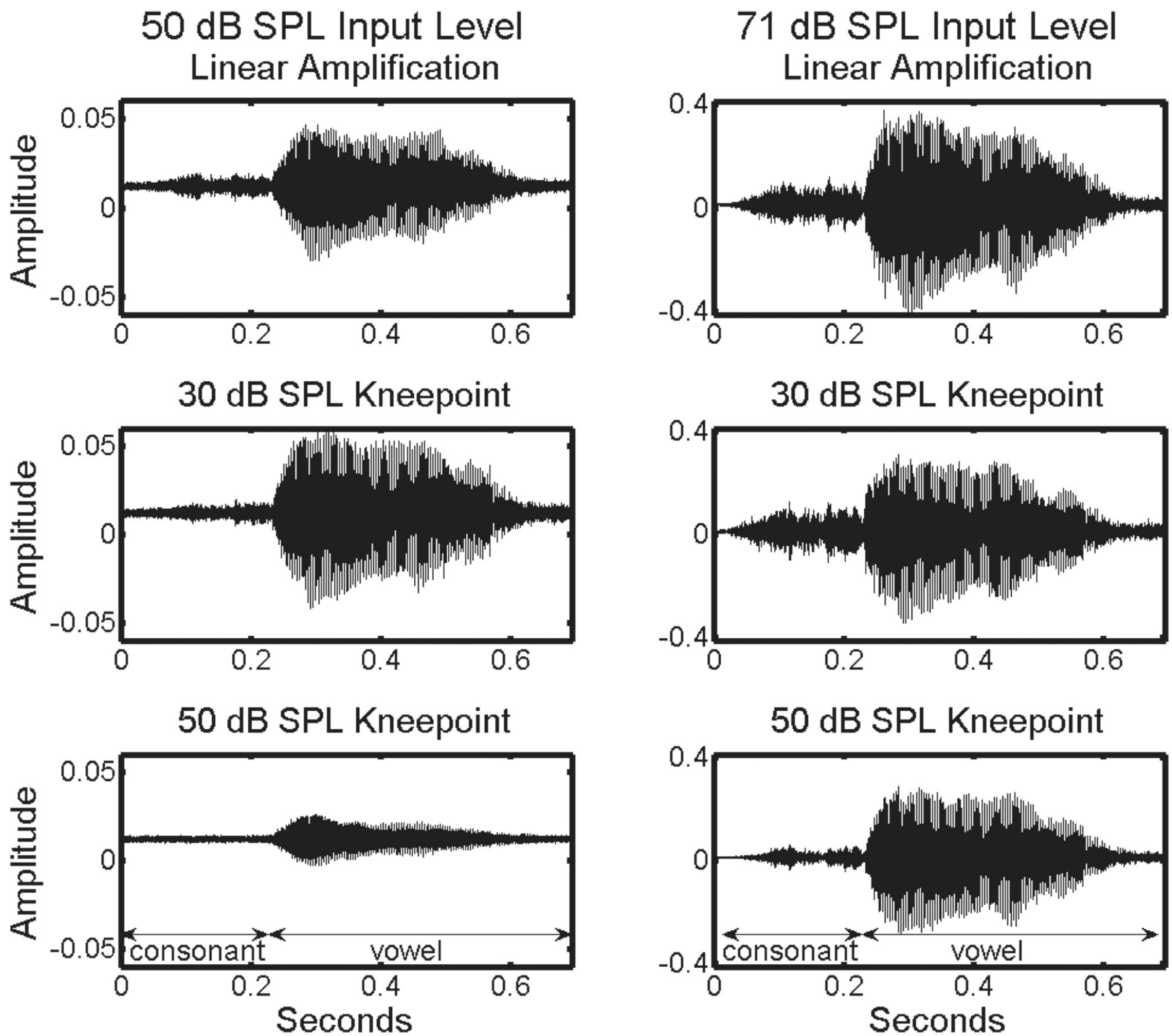

Figure 6.
Waveform plots of /si/ for subject 10. The left column is for an input level of 50 dB SPL, and the right column is for an input level of 71 dB SPL. The consonant portion and vowel portion are labeled on the bottom two graphs. Notice that the scaling is different for the two input levels.