Speech recognition at higher-than-normal speech and noise levels

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Abstract

Previous research has demonstrated reduced speech recognition of normal hearing listeners when speech is presented at higher-than-normal levels (e.g., above conversational speech levels), particularly in the presence of speech-shaped background noise. The present study examined the interactive effects of signal-to-noise ratio (SNR), noise level and filtering on word recognition in noise. Speech recognition for 10 young adults with normal hearing was assessed for broadband, highpass and lowpass filtered speech (CF 1.6 kHz) at three noise levels (62, 72 and 82 dBA). The interfering noise conditions were steady talker spectrum matched noise, and 16 Hz interrupted noise with a duty cycle of 50%. The SNRs for the broadband conditions in steady noise were -12, -9, -6, -3 and 0 dB and SNRs 0, 3 and 6 dB were selected for the highpass and lowpass conditions. In interrupted noise, the SNRs for the broadband conditions were -30, -24, -18, -12 and -6 dB and for the highpass and lowpass conditions, the SNRs were -18, -9, 0 and 6 dB. For all conditions, speech recognition performance increased with increase in SNR, except for the lowpass filtered words presented in steady noise. At the same SNR, word recognition performance in interrupted noise differed significantly from performance in steady noise across noise levels. For broadband filtered words presented in steady noise, performance slightly decreased at higher SNRs (0, -3 dB) with increasing noise level. In interrupted noise, performance increased with increasing noise level for all SNRs, with significant interactions between SNR and level. Lowpass filtered speech was more difficult to recognize than highpass filtered speech and increasing the level of lowpass filtered speech at the same SNR did not improve speech recognition.

Contents

1. General introduction

When people come to the clinic with hearing problems, the most common complaint is that they are having difficulty understanding speech in noisy environments, for example when many people are chatting at a party, or when they is a lot of traffic noise. Interestingly, clinical measurement of speech perception is done in quiet rooms. The outcomes of these tests, which usually involve repeating words presented over headphones, give an indication of how well a person is able to understand speech. However, to make the test more representative of everyday situations, a more practical test procedure should be used, evaluating speech perception in noise (e.g. Plomp, 1986; Bosman, 1989).

Making such a test a reliable tool for evaluating hearing loss requires a lot of investigation. There are many factors that can influence the outcome of the test, such as the type of material used (words, monosyllables, sentences, nonsense words etc.), the type of noise (in terms of temporal as well as spectral make-up), and the level at which the speech and noise are presented to the listener.

It is not clear what effect high speech presentation levels have on speech perception. A number of studies have suggested that word recognition is independent of presentation level through at least 90 dB SPL and is determined entirely by Signal to Noise Ratio (SNR) (e.g., Hawkins and Stevens, 1950; Hirsh and Bowman, 1953; Duquesnoy and Plomp, 1983). However, data from other studies (e.g., Pickett & Pollack, 1958; Dirks et al, 1982; Studebaker et al. 1999) suggests that speech intelligibility at any given SNR deteriorates when noise levels are high.

The experiments just described all measured speech recognition by presenting subjects with English words or sentences. In Dutch clinics, however, speech audiometry is done with Dutch word lists (NVA lists, 'Nederlandse Vereniging voor Audiologie'). For this material, it is known how well normal hearing listeners recognize speech stimuli in quiet. Consequently, evaluation of hearing loss in quiet can be performed with respect to a 'normal' curve in the speech audiogram (see Appendix I). However, there is no such reference for speech presented against different levels of noise. Since the literature indicates that there may be an interaction between signal-to-noise ratio and the level at which speech and noise is presented, the present experiment was set up to further explore the effect of level on speech perception in noise. Ten normal-hearing listeners were presented with words in noise at three intensity levels, 62, 72 and 82 dBA.

In normally hearing persons, speech recognition performance is affected less by fluctuating maskers (e.g., Festen and Plomp, 1990; Dubno, 2002) or interrupted maskers (Stuart and Phillips, 1996; Dubno, 2003) than by steady state maskers, so the masking noise of this experiment consisted of two ‘noise types’, steady noise with the long-term average speech spectrum of the talker and 16 Hz interrupted noise. In impaired hearing, temporal processing has deteriorated. This is reflected in differences in speech performance scores between hearing-impaired and normally hearing persons in fluctuating noise; the differences are much larger than with steady-state noise (Festen & Plomp, 1990; Versfeld & Dreschler, 2002; Pool, 2008).

Impaired frequency selectivity may also affect speech recognition in noise. A high-frequency hearing loss mainly affects the recognition of consonants. In order to compare performance between listeners with high-frequency hearing loss and normal-hearing listeners, the speech in the present experiment was highpass filtered. It is common to also measure the effect of lowpass filtering on speech recognition to further study the effect of the spectral make-up of the words (Molis & Summers, 2003; Dubno et al. 2005, 2006; Summers et al. 2007). Therefore, in this experiment, the words were presented as three ‘filtering types’, broadband (BB), highpass (HP) and lowpass (LP). The speech was filtered at cutoff frequency (CF) 1600 Hz. Speech recognition was measured at a number of different SNRs that would give recognition scores between 30% and 80% (to avoid ceiling effects). A pilot study was conducted to find SNRs which would give scores within this range. SNRs -12, -9, -6, -3, and 0 dB emerged as the most suitable SNRs for measuring speech recognition performance of broadband words in steady noise. In interrupted noise, the SNRs were -30, -24, -18, -12, and -6 dB. The highpass and lowpass filtered words were presented in steady noise at SNRs 0, 3, and 6 dB and in interrupted noise at SNRs -18, -9, 0 and 6 dB.

In order to fully understand the theoretical background of the experiment, a concise introduction into speech audiometry is needed. That is the purpose of the following section. After this section, a short overview of relevant literature is presented, followed by the description of the actual experiment.

2. Practical Background

2.1 Speech audiometry

Audiologists wish to determine how well a person hears/understands speech at different intensities. Word recognition testing, or speech audiometry, provides a relative measure of a person's speech perception ability. In the clinic, the standard procedure is as follows. The subject is presented with a number of short words (usually eleven, a so-called word list) at different intensity levels and is instructed to repeat the words he or she hears. The first list is presented at an intensity of which the audiologist is sure the subject can hear all the words (based on the measured hearing thresholds in prior tone audiometry). The number of correctly repeated phonemes is counted, with 33 phonemes counting as 100%. Then, the next list is presented at an intensity level which is 10 dB lower, and so on. The result is a speech audiogram (see bottom Appendix I), which is the number of correctly repeated phonemes plotted as a function of intensity level.

In the pure-tone audiogram (PTA, top of Appendix I), the sensitivity of the auditory system is plotted as a function of frequency. However, the audiogram does not provide information on psychophysical measures like frequency or time resolution, spread of masking etc. in the auditory system. As speech is a complex stimulus with variations both in the time and frequency domain, speech audiometry is a useful tool that can provide insight into the overall performance of the auditory system (Moore, 2007).

2.2 Relationship between tone and speech audiogram

As already said above, an example of a tone- and speech audiogram is included in Appendix I. At the top, the tone audiogram is depicted. It is a graph showing the hearing threshold levels as a function of frequency. The 0 dB HL line is the average hearing threshold of young, normal-hearing listeners. A hearing loss of 5 dB HL at 1000 Hz means that a person just hears a 1000 Hz tone at an intensity that is 5 dB higher than an average normal-hearing person. The average hearing loss of a person at 500, 1000 and 2000 Hz is called the Fletcher index. There is a relationship between the Fletcher index and the Speech Reception Threshold (SRT), which can be read from the speech audiogram (bottom of App. I). The SRT is the intensity at which the subject is able to correctly repeat 50% of the presented phonemes. In the example in the Appendix, the SRT for the right ear is at 30 dB. The left curve in the speech audiogram is the average curve of normal hearing listeners, with an average SRT of 25 dB. The Fletcher index of the right ear is 5 dB, which is the same number of dB's the speech curve has shifted to the right compared to the average curve. The shift and form of the speech curve are indicative of the type of hearing loss. When an elevated hearing threshold is found with tone audiometry and in addition, the speech recognition curve is shifted to the right away from the normal curve (which is conform to the Fletcher index), there is an indication of conductive hearing loss. With this type of hearing loss, 100% correct phoneme score will be reached if the words are presented well above the (elevated) hearing threshold. However, if a person is unable to reach the 100% score at intensities above the hearing threshold, this is a sign of possible retro-cochlear hearing loss, and further testing is needed (Marshall & Bacon, 1981).

2.3 Speech material

As explained in the previous sections, speech audiometry serves two different purposes: the assessment of impairment in auditory communication and the diagnosis of hearing loss. For testing impairment in auditory communication, speech materials should be used that closely resemble real-life speech. "Real-life" speech covers a wide range of materials and it is heard under a variety of conditions, so in order to obtain a good insight into the communicative abilities of the hearing impaired, large numbers of test materials with different acoustic and linguistic properties should be used. Extensive testing, however, takes a lot of time, which is scarce in clinical practice, so tests can only focus on a few aspects of speech reception.

For diagnosis of hearing loss, the ability to discriminate between normal hearing and hearing-impairment is of primary importance. This is based on auditory sensitivity. In order to measure sensitivity, test items should have little redundancy, to rule out top-down processing as much as possible. Testing happens in a soundproof booth with mono- or disyllabic words (Bosman, 1989).

There is a clear effect of the speech material on the steepness of the performance intensity function and thus, on the accuracy of estimating the 50% point (the steeper the more accurate). The effect of speech material on the steepness of the performance intensity function is illustrated in Fig. 1.

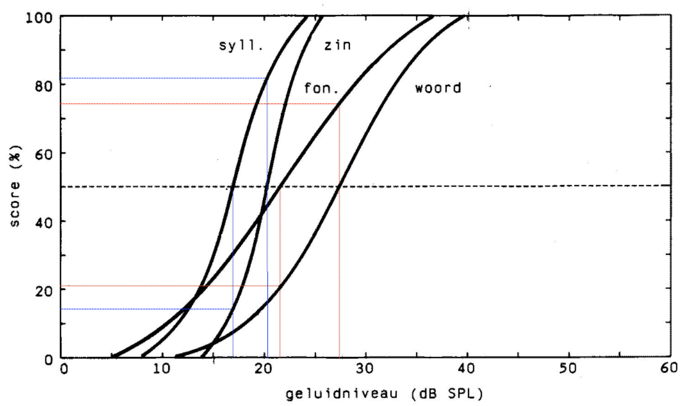


Figure 1. Performance Intensity functions for word, phoneme, sentence and syllable material. Material is spoken by a female Dutch speaker.

On the x-axis, the sound level is represented and the y-axis represents the percentage correct score. Keeping in mind that the conversational level of speech is at about 65-70 dB SPL, a number of comparisons between these curves can be made.

First, the relationship between phoneme (fon.) and word (woord) intelligibility can be described (see the red lines in Figure 1):

- A phoneme score of 50% corresponds to a word score of 21%. If 50% of the words are recognized correctly, the percentage correctly recognized phonemes is 74%.
- The intensity level at which 50% of the phonemes are recognized correctly is 22 dB SPL. To recognize 50% of the words, the intensity has to increase by 5 dB to 27 dB SPL.

Second, a comparison can be made between syllable* (syll.) and sentence (zin) intelligibility (see the blue lines in Fig.1):

- A syllable score of 50% corresponds to a sentence score of 14%. If 50% of the sentences are recognized correctly, the syllable score is 82%.
- The level at which 50% of the syllables are recognized correctly is 17 dB SPL. The intensity has to increase by 3.5 dB to 20.5 dB SPL for 50% correct sentence recognition.

Third, the curves can also be compared in terms of the range over which performance increases from 0 to 100% correct score:

- The phoneme score (fon.) is 100% at 37 dB SPL and 0% at 5 dB SPL. The range from minimum to maximum recognition is 32 dB.
- A 100% correct word score (woord) is reached at 39 dB SPL. At 12 dB SPL, none of the words were recognized, so the dB range from 0 to 100% recognition is 27 dB.
- The syllable score (syll.) increases from 0% at 8 dB SPL to 100% at 23.5 dB SPL. The range from minimum to maximum recognition is 15.5 dB.
- The range of the sentence score (zin) is (0% at 13.5 dB SPL and 100% at 25.5 dB SPL) 12 dB.

In clinics, all four kinds of scores are used to measure speech recognition. It is therefore interesting to make comparisons between phoneme and word recognition or syllable and sentence recognition and find out if the one can be predicted from the other. The third comparison clearly shows the effect of speech material on the steepness of the PI function. The range over which performance goes from minimum to maximum is smallest for sentences (12 dB) and biggest for phonemes (32 dB). The reason for that is that sentences contain a lot

* Here, the term ‘syllable’ is used for sense CVC syllables, which would be more commonly referred to as ‘monosyllabic words’.

of redundant information, which makes them the easiest speech material to recognize. The smallest unit, the phoneme, contains the least speech information, so it is hard to recognize it correclty. Taken together, the speech material used has a clear effect on intensity level needed for 50% correct recognition and the steepest PI function is obtained when sentences are used.

2.4 Speech in noise

From the previous section it follows that sentences are more suitable for determining the SRT than words. This is not the only advantage of using sentences in speech perception tests; they also resemble "real life" speech perception more than isolated words. Another characteristic of "real life" speech perception is that it does not occur in quiet surroundings, like a sound proof booth. A common complaint of (mostly) elderly people is that they have trouble understanding speech in background noise or when many people talk at the same time. This means that the measures obtained under optimal listening conditions (a sound proof booth and words presented in quiet over headphones) are often not comparable with the patients' self-reported disability. Therefore, Plomp and Mimpen (1979) presented a more practical test procedure. The test consists of 13 sentences. First, the sentences are presented in quiet to determine SRTq. The first sentence is presented at a level well below the hearing threshold as measured with tone audiometry, so the sentence is not heard. Then, the level of the first sentence is increased by 4 dB until the whole sentence is repeated correctly by the subject. Next, the second sentence is presented at a level which is 2 dB lower. If the sentence is repeated correctly, the level for the next sentence is decreased by 2 dB. If it is not repeated correctly, the same sentence is presented at a level which is 2 dB higher. Following this adaptive procedure (for more up-down methods see Levitt, 1970), the SRTq is determined by taking the average change in intensities over the last 10 sentences plus the intensity that a 14th sentence would haven been presented at. Its value is expressed in dB(A)* . It is the intensity of speech needed to correctly repeat 50% of the sentences. To determine the SRT in noise, the sentences are presented in steady noise. The noise level is 15 to 20 dB above the SRT in quiet, with a minimum of 60 to 65 dB SPL and as a maximum 75 dB SPL. The first sentence is presented at the subject's SRTq. Now, noise is presented simultaneously, so the sentence is masked and the subject cannot repeat it correctly. The level of the sentence is then increased

* A sound expressed in decibel A-weighted (dBA) means that an 'A-filter' is applied to the input to imitate the frequency-dependent sensitivity of the human ear. As a consequence, sounds of equal dBA sound equally loud to a normal hearing listener, regardless of their frequency.

with 4 dB steps until it is repeated correctly. The subsequent procedure is the same as SRT measurement in quiet. The value of the SRT in noise is expressed as the Signal to Noise Ratio (SNR) needed in order to repeat 50% of sentences presented in noise correctly.

3. Theoretical background

The study of speech intelligibility in noise has a long history. It is generally agreed that noise has a clear effect on the performance of the listener, but exactly how this effect depends on the type of noise and the task being performed is not clear. In the present study, we are interested in the effect of high presentation levels, noise type, and filtering on word recognition by normal hearing listeners. A number of studies have looked at these effects on recognition of English word lists. The most relevant ones will be described in the following sections, followed by the choices that were made for the conditions of the present study.

3.1 Effect of high levels on performance

A number of studies have suggested that word recognition is independent of level through at least 90 dB SPL and is determined entirely by SNR (e.g., Haskins and Stevens, 1950; Hirsh and Bowman, 1953; Duquesnoy and Plomp, 1983). Other studies, however, suggests that speech intelligibility deteriorates when noise levels are high and SNRs are constant.
Studebaker et al. (1999) presented bandpass filtered (447-2239 Hz) word lists (monosyllabic words) at speech levels ranging from 64 to 99 dB SPL at SNRs ranging from 28 to -4 dB in talker spectrum matched noise. Their results are presented in Fig. 2.

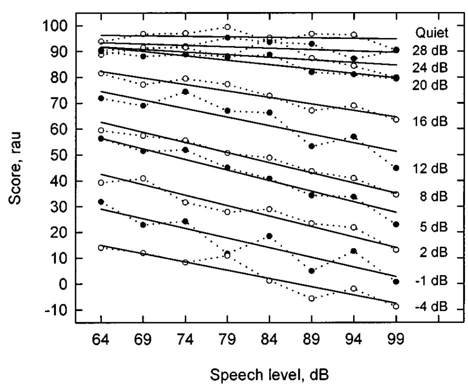


Figure 2. Mean word-recognition scores (in rau) plotted as a function of speech level for normal-hearing subjects (image taken from Studebaker (1999)) with straight lines fit to the mean word recognition scores.

Each function in the figure displays the results at a different and constant SNR. The recognition scores were transformed into rationalized arcsine units (rau) to equalize speech recognition score variance between test items (see Studebaker, 1985; Sherbecoe & Studebaker, 2004 for details). Figure 2 shows that the functions decline substantially as the speech and noise levels increase. For SNR 12 dB, the word score declines from 72 rau at 64 dB SPL to 45 rau at 99 dB SPL, which means a decline of 27 rau. At an SNR 8 dB, increasing the speech level from 64 to 99 dB SPL leads to a decrease in score of 24 rau. At SNR 5 dB the decrease is 35 rau. Obviously, performance declines substantially with increasing level and there is an interaction between level and SNR.

For the present study, a pilot study was conducted to find noise levels and SNRs that would give percentage correct scores between 30% and 80%. Within this range, clear effects will show up, because floor and ceiling effects are avoided. Based on existing PI functions of word and phoneme recognition of the NVA lists in steady noise by normal hearing listeners (see Fig. 3 and Fig. 4), three independent listeners were presented broadband, highpass and lowpass filtered words in steady noise at 60 and 80 dBA and SNRs -12, -9, -6, -3, 0, 3, and 6 dB. Interrupted noise was also presented at the same noise levels and broadband, highpass and lowpass filtered words were presented at SNRs -30, -24, -18, -12, -8 and -6. Since we wanted to measure performance at the high noise levels, we also presented two listeners with noise levels of 82 dBA and 85 dBA. Speech presented at SNR 0 dB with noise level 82 dBA was judged to be the highest acceptable level. It is expected that this level is high enough to find level effects. Based on this pilot study, in the present study the broadband speech stimuli are presented in steady noise at 62, 72 and 82 dBA with SNRs of -12, -9, -6, -3 and 0 dB, which gives speech levels that are comparable to the ones used in Studebaker (1999).

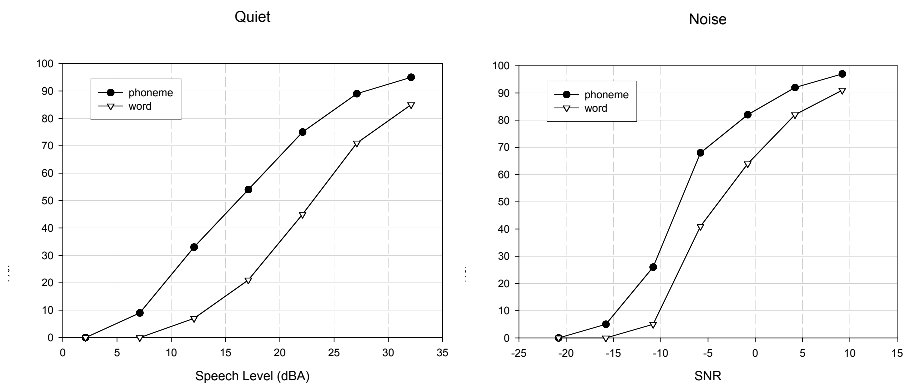


Figure 3 and figure 4. Phoneme and syllable (word) scores with CVC words (NVA word lists) in quiet (left picure) and in noise (right picture) of a group of normal hearing listeners (replotted data from Bosman & Smoorenburg (1995) p. 274). Noise levels were 60 dBA.

3.2 Effect of noise type on performance

A noise background can be characterised in terms of its average level, its frequency content and its fluctuation. Many studies of speech intelligibility have used white noise as a masker (e.g., Hawkins and Stevens, 1950; Keith and Talis, 1972). A masking noise with the long-term average spectrum of a speech corpus (e.g., Bosman, 1989; Rhebergen et al., 2008a) is also used, for it can mask the speech signal more effectively than white noise.

Many studies have found that in normally hearing persons, speech recognition performance is affected less by fluctuating maskers (e.g., Festen and Plomp, 1990; Dubno, 2002) or interrupted maskers (Stuart and Phillips, 1996; Dubno, 2003) than by steady state maskers. One explanation for these findings is that normal hearing persons can make use of the momentary improvements in SNR. This ability is much smaller or absent in patients with sensorineural hearing loss (Summers & Molis, 2004; Jayaram et al., 1992). As a result, the differences in speech performance scores between hearing-impaired and normally hearing persons are considerably larger with fluctuating noise than with steady-state noise (Festen & Plomp, 1990; Versfeld & Dreschler, 2002; Pool, 2008).

In the present study, two types of noise are used: steady state noise that matches the long term average speech spectrum of the NVA ('Nederlandse Vereniging voor Audiologie') word lists and 16Hz interrupted noise with a duty cycle of 50% (Rhebergen, 2006). Broadband stimuli are presented in interrupted noise at SNRs of -30, -24, -18, -12, -6 dB. SNR -6 dB and -12 dB are the same in the steady state noise and interrupted noise. These two SNRs can be used to compare the performance scores in the two different noises. Based on studies just described, it is expected that performance will be higher in interrupted noise than in steady noise across noise level (e.g., de Laat & Plomp, 1983; Pool, 2008) and there will be an interaction between SNR and level on performance in interrupted noise.

3.3 Effect of spectral composition on performance

To examine if the decline in word recognition performance at high speech and noise levels is a purely broadband phenomenon or whether it is frequency dependent, Molis and Summers (2003) presented listeners with normal hearing with sentences that were highpass filtered at cutoff frequency 750 Hz or lowpass filtered at cutoff frequency 2750 Hz in quiet at two intensity levels, 85 and 105 dB SPL. The increase in intensity from 85 to 105 dB SPL produced a greater decline of performance for the high-frequency sentences compared to the lowpass sentences. Word recognition of high and lowpass filtered words in highpass and lowpass filtered noise (the same cutoff frequencies were used for the noise as for filtering speech) was examined by Dubno et al. (2005, 2006). They presented normal hearing adults with lowpass (CF 0.16 to 2.08 kHz) and highpass (CF 2.08 to 7.40 kHz) filtered words and nonsense syllables in low- and highpass speech-shaped maskers at three speech levels (62-94 dB SPL) for three signal-to-noise ratios (+8, +3 and -2 dB). In contrast to Molis and Summers (2003), they did not find any level dependent differences in speech recognition between low- and high frequency speech. Summers et al. (2007) presented normal-hearing and hearing-impaired listeners with low- and high frequency (CF 1500 for lowpass, CF 2000 for highpass) sentences in noise at high presentation levels (speech levels 75, 87.5 and 100 dB SPL). For normal-hearing listeners, performance decreased as levels increased. This effect was greater for high-frequency and broadband materials than for low-frequency materials. For hearing-impaired listeners, the 75 to 87.5 dB increase improved signal audibility for high-frequency stimuli and no decrease in performance was observed. The 87.5 to 100 dB increase, however, produced a decrease in performance similar to the normal hearing group: scores decreased more for high-frequency sentences and least for low-frequency materials.

To further examine level dependent spectral effects, the present study included words that were highpass (HP) and lowpass (LP) filtered. A pilot study was conducted on three normal hearing listeners. Its aim was to find a cutoff frequency that would produce equal performance across level and SNR. Based on the literature described above, performance at CF 1600, 1800 and 2000 was measured at a number of SNRs. The results of the pilot showed that recognition of the NVA word material was about equal at a cutoff frequency of 1600 Hz. The SNRs used in the HP and LP conditions are 0, 3, and 6 dB in steady noise and -18, -9, 0 and 6 dB in interrupted noise. SNRs 0 and 6 dB can be used for comparison between noise types, and all SNRs between the two filter types can be compared. It is expected that increase in level will decrease performance in steady noise for both HP and LP and this decline will be greater for the HP filtered words than for the LP filtered words. Performance in interrupted noise will be better than performance in steady noise across SNRs and an interaction between level and SNR is expected.

4. Research Questions and Purpose

The main question that we would like to get an answer to is: what is the effect of high speech and noise levels, noise type (steady and interrupted noise) and filtering (highpass and lowpass) on the speech recognition of Dutch word lists (NVA lists) by normal hearing listeners?

The obtained knowledge can be used for the extension of the speech intelligibility index (SII; ANSI, 1997) in order to make better predictions of how well hearing-impaired listeners can understand speech in different noisy environments. Also, the knowledge is useful for the development of more sensitive and specific audiometric tests.

5. Experimental Design

5.1 Subjects

A group of 10 normal-hearing subjects with an age range of 18 to 28 years (mean age: 21.4 yrs.) with no history of audiological pathology were tested on their best ear, based on audiometry. Pure tone thresholds were no poorer than 20 dB for frequencies from 240 Hz to 8 kHz and all had a maximum speech recognition score of 100% in quiet.

Fig. 5 reports the mean hearing-threshold data for all subjects. The threshold data are based on clinical audiometric measurements obtained using a step size of 5 dB SPL.

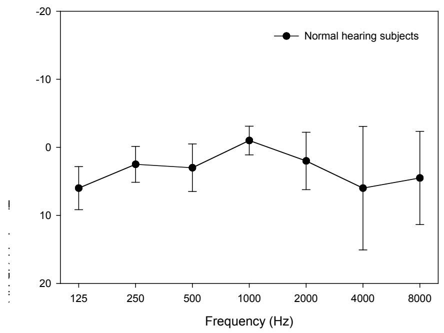


Figure 5. Mean thresholds for pure tones measured in quiet for 10 normal hearing subjects. Error bars indicate the standard deviation of the mean threshold (SD).

5.2 Apparatus and Stimuli

The stimuli were broadband, highpass and lowpass CVC words presented in stationary and 16 Hz interrupted talker-spectrum-matched noise. The overall noise levels were fixed at 62, 72 and 82 dBA and SNRs ranged from -30 to 6 dB. In order to compensate for the gaps in the noise in interrupted noise, the noise level of the noisy periods was 3 dB higher than the overall level of the steady noise condition. Table I reports the conditions presented to each listener.

Fixed noise level 62, 72, 82 dBA	**SNR (dB)**
Broadband Steady Interrupted	 -12, -9, -6, -3, 0 -30, -24, -18, -12, -6
Highpass Steady Interrupted	 0, 3, 6 -18, -9, 0, 6
Lowpass Steady Interrupted	 0, 3, 6 -18, -9, 0, 6

Table I. All conditions presented to each listener.

The speech materials were copies of the 'Woordenlijst voor Spraakaudiometrie' recordings (Bosman (1989)), spoken by a female talker. Each list consists of twelve monosyllabic words constructed from the same pool of twelve initial consonants, twelve vowels, and twelve final consonants. The words were lowpass or highpass filtered at a cutoff frequency of 1600 Hz with a Matlab™ Fir1, 2000 order (Version 5.3, The Mathworks, Inc.) implementation. The SNRs of the lowpass and highpass filtered conditions are the SNRs before filtering, so the overall speech level of the HP and LP filtered conditions are lower than that of the BB conditions. The maskers were stationary and 16 Hz interrupted random noise that had been digitally filtered so that its long-term RMS spectrum matched the levels of the talker's short terms speech spectrum.

5.3 Procedure

Equipment calibration was performed at the start of the experiment. Subjects were told that they would hear words distorted by noise and they were instructed to say aloud what they heard. It was explained that some of the words would be hard to understand, and that they should make their best guess at as many words or speech sounds as possible.

The word lists were completely randomized across conditions and subjects. Since there are 72 conditions but only 60 different NVA word lists (one list needed for each condition), twelve random word lists were presented twice.

One session of two hours consisted of three parts. One part consisted of the conditions presented at one particular noise level (62, 72 or 82 dBA). The order of these parts was completely randomized between subjects. Within one part, three filtering types (BB, HP and LP) are presented. Each part always started with the BB words (the least difficult ones, to get the subject motivated) followed by the HP/LP or LP/HP filtered words. The order HP/LP or LP/HP was randomized across parts and subjects. Noise type (steady or interrupted) was randomized within the filtering conditions.

No feedback was given during the experiment, which took approximately four hours (2 hours per session). The retest was two days to one week after the test, depending on the subject's availability.

The stimuli were presented monotically to the subject's best ear over Sennheiser HDA200 headphones. The stimuli were played out via a RME Fireface 800 sound card at 24 bit resolution with a sampling rate of 44.1 kHz.

5.4 Data treatment

Answers the subjects were scored by the experimenter with computer software that was developed at the AMC for this experiment. The word that was presented to the subject was visible for the experimenter on a screen as three separate phonemes, and the experimenter clicked on the phonemes that were repeated correctly. The percentage of phonemes for each condition (so the number of correctly repeated phonemes per word list) was calculated automatically. A word was correct if all three phonemes were repeated correctly. The first word of a word list was for familiarization, so the final score for each list was the percentage of correct responses to 33 phonemes (a word list is made up of twelve words consisting of three phonemes each).

6. Analysis and Results

To deal with the sphericity assumption underlying analysis of variance (Max & Onghena, 1999), the distribution of the data was normalized by transformation of the data into rationalized arcsine units (rau) before any statistical analysis (Studebaker, 1985; Studebaker et al, 1995; Sherbecoe & Studebaker, 2004).

Statistical Analysis of Variance (ANOVA) revealed that for all conditions, the difference in performance between test and retest was significant ($p<.048$). Performance in the retest was significantly better. Therefore, only the data of the retest was used for further analysis.

6.1 Broadband conditions

Fig. 6 and Fig. 7 show the mean word scores for the broadband conditions in stationary and 16 Hz interrupted noise, plotted as a function of noise level. Each function displays the results at a specific SNR. Fig. 6 shows that at lower SNRs (SNR -12, -9 and -6 dB) in steady noise, word recognition performance increases as the noise level increases from 62 to 72 dBA and then decreases as the noise level increases further to 82 dBA. At higher SNRs (SNR -3 and 0 dB), performance decreases when the speech and noise levels are increased from 62 to 82 dBA; at 62 dBA, performance score at SNR 0 is 89 rau and and at 82 dBA the score is 78 rau. For SNR -3 the score at 62 dBA noise level is 79 rau and at noise level 82 dBA the score decreases 69 rau. Fig. 7 shows that, when the noise is 16 Hz interrupted, increase in speech and noise levels from 62 to 82 dBA has an increasing effect on performance for all SNRs. Also, there is an interaction between SNR and level. At SNR -30, the score increases from 54 rau (from 1 to 55 rau) as the noise level increases from 62 to 82 dBA. For SNR -6, this increase is only 15 rau (from 86 to 101 rau).

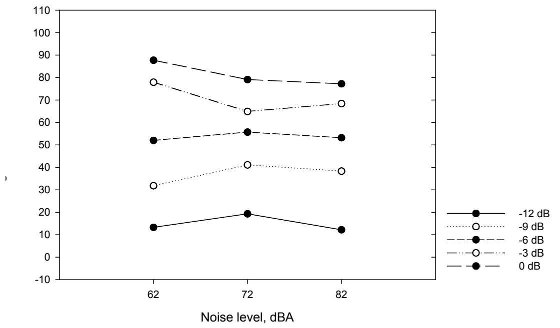


Figure 6. Broadband, Steady, Word

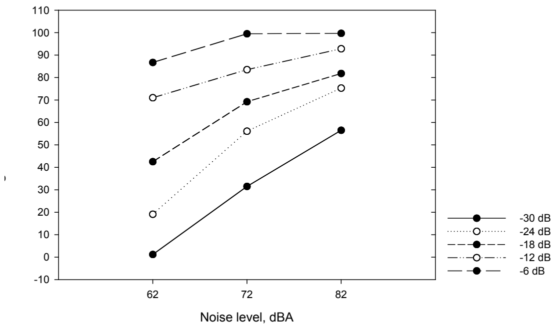


Figure 7. Broadband, Interrupted, Word

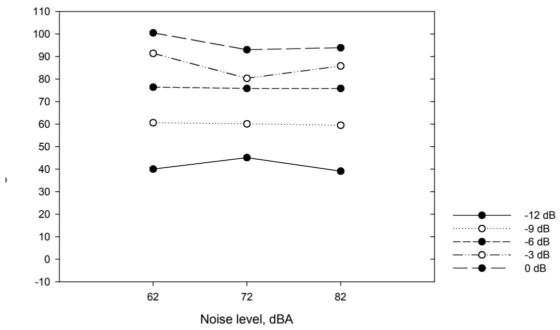


Figure 8. Broadband, Steady, Phoneme

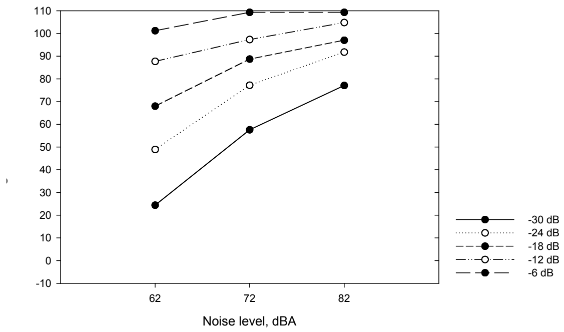


Figure 9. Broadband, Interrupted, Phoneme

Fig. 8 and Fig. 9 show the phoneme scores for the broadband conditions in stationary and 16 Hz interrupted noise. As expected, both figures show that the overall rau scores are higher than the word scores. Fig. 8 shows that in steady noise, phoneme recognition performance remains equal at lower SNRs (-12, -9, -6 dB) as the noise level increases from 62 to 82 dBA. At the higher SNRs (-3 and 0 dB), performance decreases as the noise level increases from 62 to 82 dBA. Fig 9 shows that, in interrupted noise, the phoneme score increases for all SNRs. The biggest effect is visible for the lower SNRs (-30, -24, 18 dB). At SNR -30, the score increases from 24 rau at 62 dBA noise level to 76 rau at 82 dBA noise level.

Fig. 10 and Fig. 11 show the results of the broadband word conditions in a more conventional way, with the mean scores obtained at each noise level replotted as a function of SNR. The separation of the different functions in Fig. 9 compared to Fig. 8 clearly shows the effect of overall speech and noise level on performance in interrupted noise.

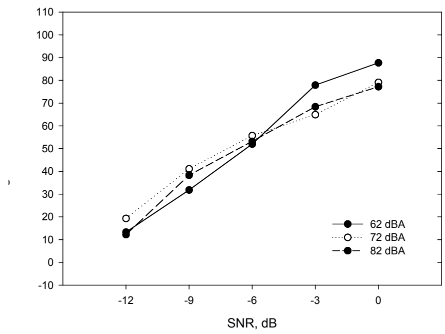


Figure 10. Broadband, Steady, Word

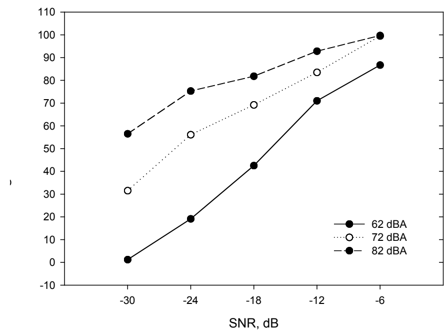


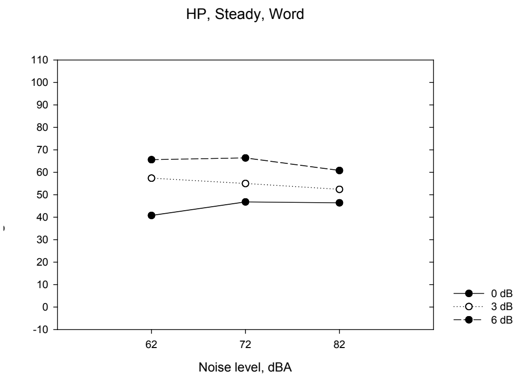
Figure 11. Broadband, Interrupted, Word

A 3[noise level] x 8[SNR -12, -9, -6, -3, 0, -30, -24, -18] x 2[noise type] x 2[score type] Analysis of Variance (ANOVA) revealed a significant effect of score type (F[1,540]=252.28, p=.000) on rau score. The phoneme score was significantly higher than the word score. Separate 3[noise level] x 5[SNR -12, -9, -6, -3, 0] ANOVA revealed that for the Steady Word and Steady Phoneme conditions, there is a significant effect of SNR (F[4,135]=107.0, p=.000 and F[4,135]=137.21, p=.000 respectively). For the Interrupted Word and Interrupted Phoneme conditions, 3[noise level] x 5[SNR -30, -24, -18, -12, -6] ANOVA's revealed that there is a significant effect of SNR (F[4,135]= 53.52, p=.000 and F[4,135]= 68.38, p=0.000) and of noise level (F[2,135]= 46.99, p=.000 and F[2,135]= 60.70, p=.000) on rau score. There are significant interactions between SNR and noise level in the Interrupted Word conditions (F[8,135]= 2.6, p=0.01) and also in the Interrupted Phoneme conditions (F[8,135]= 4.4, p=.000).

For SNR -6 dB, 3[noise level] x 2[noise type] x 2[score type] Analyses Of Variance reveal a significant effect of noise type on both word ($F[1,54]= 256.24$, $p=.000$) and phoneme ($F[1,54]= 350.99$, $p=.000$) rau score. The effect of noise type on word ($F[1,54]= 116.46$, $p=.000$) rau score and phoneme ($F[1,54]= 158.07$, $p=.000$) was also significant for SNR -12 dB.

6.2 Highpass conditions

The results of the highpass filtered conditions are reported in Figs. 12 and 13.



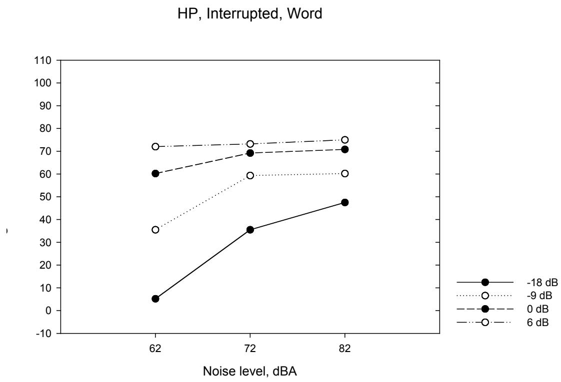
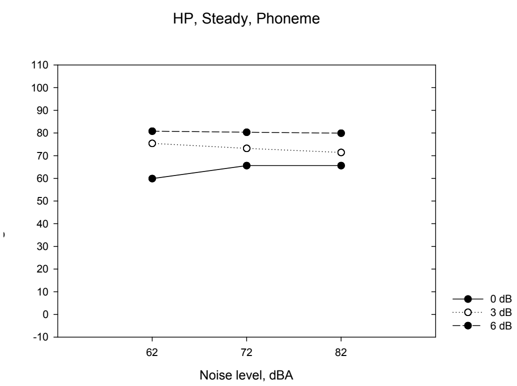


Figure 12. Highpass, Steady, Word　　*Figure 13. Highpass, Interrupted, Word*

Fig. 12 shows that there is a clear effect of SNR but not of level. In Fig. 13, again a clear effect of level on speech recognition performance in interrupted noise shows up and there is also an interactive effect of SNR and Noise Level; at SNR 6, there seems to be a ceiling effect, whilst at SNR -18, performance increases from 5 to 45 rau.

The phoneme scores in the HP conditions depicted as a function of noise level in Fig. 14 and Fig. 15 resemble the word scores to a great extent. The major difference, as expected, is that overall, the scores are higher for all SNRs.



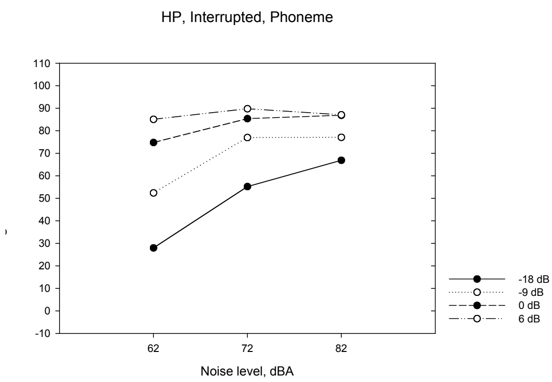


Figure 14. Highpass, Steady, Phoneme　　*Figure 15. Highpass, Steady, Phoneme*

A 3[noise level] x 5[SNR 0, 3, 6, -9, -18] x 2[noise type] x 2[score type] Analysis of Variance revealed a significant effect of score type (F[1,378]=171.72, p=.000) on rau score. Further analyses with 3[noise level] x 3[SNR 0, 3, 6] ANOVA's reveal that, for the the Steady Word and Steady Phoneme conditions, the effect of SNR on rau score is significant (F[2,81]=17.18, p=.000 and F[2,81]=21.23, p=.000 respectively). For the Interrupted Word and Phoneme conditions, 3[noise level] x 4[SNR -18, -9, 0, 6] ANOVA's reveal that SNR (F[3,108]=45.81, p=.000 and F[3,108]=45.74, p=.000 respectively) and noise level (F[2,108]=18.26, p=.000 and F[2,108]=24.32, p=.000 respectively) are significant. In interrupted noise, there is a significant interaction between SNR and level on word rau score (F[6,108]=3.37, p=.004) and phoneme rau score (F[6,108]=3.75, p=.002).

For SNR 0 dB, A 3[noise level] x 2[noise type] x 2[score type] Analysis Of Variance reveals a significant effect of noise type on both word (F[1,54]= 35.97, p=.000) and phoneme (F[1,54]= 44.84, p=.000) rau score.

Noise type also has a significant effect for SNR 6 dB, on both word (F[1,54]= 7.78, p=.007) and phoneme (F[1,54]= 6.83, p=.012) rau scores.

6.3 Lowpass conditions

The average rau scores for the lowpass conditions are presented in Fig. 16 and Fig. 17.

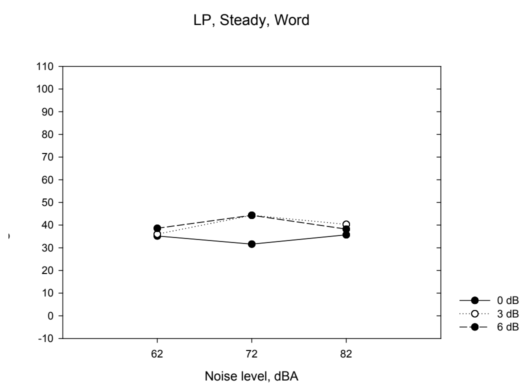


Figure 16. Lowpass, Steady, Word

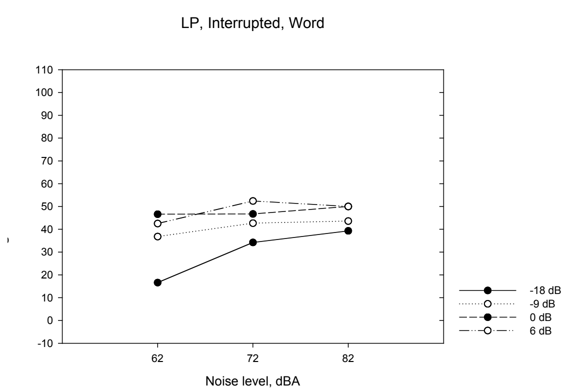


Figure 17. Lowpass, Interrupted, Word

Fig. 16 shows that performance is almost equal at SNRs 3 and 6 dB. At these SNRs performance decreases when the level increases from 72 to 82 dBA. SNR 0 dB shows a different pattern. Overall, performance is less and there even is a slight increase in performance when the level increases from 72 to 82 dB. Fig. 17 clearly shows an effect of level on performance, but this effect is not as large as in the BB and HP conditions.

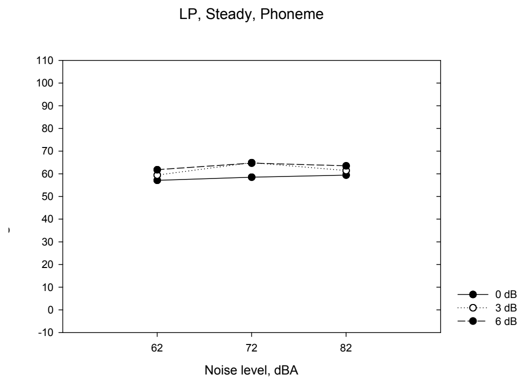


Figure 18. Lowpass, Steady, Phoneme

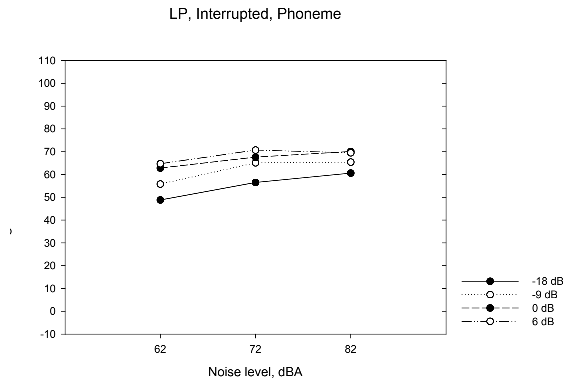


Figure 19. Lowpass, Interrupted, Phoneme

Figures 18 and 19 show the phoneme scores in steady and interrupted noise. The results do not really show a different picture from those of the word scores. There is a level effect in interrupted noise but not in steady noise, and this effect seems to be the same across SNR.

A 3[noise level] x 5[SNR 0, 3, 6, -9, -18] x 2[noise type] x 2[score type] Analysis of Variance revealed a significant effect of score type (F[1,378]=387.46, p=.000) on rau score. In steady noise, there are no significant effects of SNR or level. For the Interrupted Word and Phoneme conditions, 3[noise level] x 4[SNR -18, -9, 0, 6] ANOVA's reveal that the effects of SNR (F[3,108]=12.40, p=.000 and F[3,108]=8.49, p=.000 respectively) and noise level (F[2,108]=6.60, p=.002 and F[2,108]=6.69, p=.002 respectively) are significant. There are no significant interactions between SNR and noise level.

For SNR 0 dB, a 3[noise level] x 2[noise type] x 2[score type] Analysis Of Variance reveals a significant effect of noise type on both word (F[1,54]= 17.38, p=.000) and phoneme (F[1,54]= 10.47, p=.002) rau score.

For SNR 6 dB, the same type of ANOVA reveals a significant effect of noise type on both word (F[1,54]= 6.57, p=.013) and phoneme (F[1,54]= 6.04, p=.017) rau score.

A 2[SNR 0/6] x 2[HP/LP] x 3[noise level] x 2[noise type] Analysis Of Variance revealed that in steady noise, the difference in rau scores between the highpass and lowpass conditions is significant for Word (p=.000) and Phoneme scores (p=.034). The same goes for the interrupted noise conditions; the differences between for Word (p<.000) and Phoneme scores (p=.003) are significant.

6.5 Performance in quiet and noise

In Fig. 20, the average speech audiogram in quiet of the group of normal hearing listeners is depicted, together with the results of the broadband conditions in steady and interrupted noise.

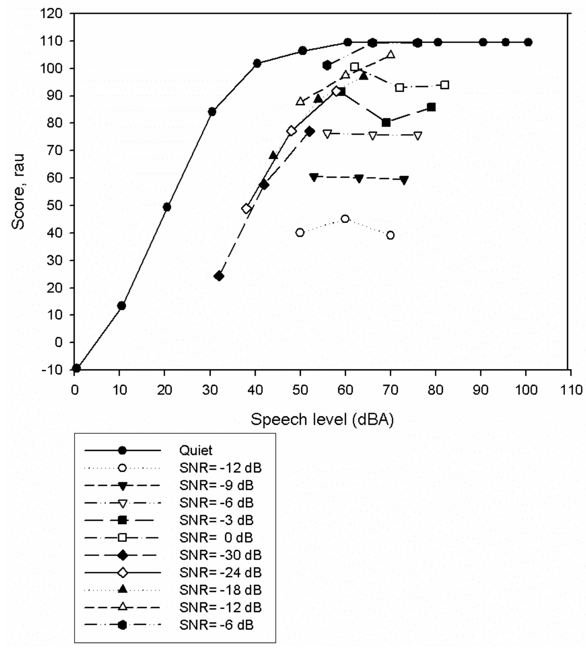


Fig. 20. Mean rau score as a function of speech level (dBA) for normal hearing listeners, in quiet, steady and 16 Hz interrupted noise.

In the figure, the horizontal lines present performance in steady noise for one SNR (SNRs -12 to 0 dB). The almost vertical lines to the left of these horizontal lines represent performance in interrupted noise (SNRs -30 to -6 dB). On the x-axis, the speech level in dBA is set out. The speech audiograms in quiet were administered at levels 9.5 dB lower than indicated on the audiogram in App. I. Therefore, 9.5 dB was substracted from the level at each point measured to get the level in dBA. Also, the percentage correct scores measured in quiet were converted into rau scores. The speech levels in dBA of the performance measured in noise were calculated by substracting the SNR (dB) from the noise level in dBA. For example, take the mean performance at SNR -12 dB in steady noise (the bottom horizontal line). At 62 dBA noise level, the speech level is 50 dBA, at 72 dBA noise level, the speech level is 60 dBA and at 82 dBA noise level, the speech level is 70 dBA.

The figure shows that adding noise to speech has a clear masking effect on speech recognition performance. When speech is presented in quiet at 35 dBA, the score is 95 rau. If interrupted noise is added, performance drops to 35 rau. Also, the figure shows that if speech is presented

in quiet at conversational level (around 60 dBA), the speech recognition score is at maximum. However, if steady noise with a level of 72 dBA is added, performance is only 45 rau.
The difference between performance in quiet and performance in interrupted noise decreases with increasing speech level. When speech is presented in steady noise, however, this difference seems to increase with increasing level at high SNRs (-3 and 0 dB).

7. Discussion

The results of the present study show effects of increases in speech and noise levels on speech recognition performance under conditions in which the SNR remains constant. The strongest effects were observed for the broadband conditions in interrupted noise. This finding agrees with that of earlier studies that have suggested that normal hearing listeners can make effective use of momentary improvements in SNR when listening to speech in interrupted maskers (Dubno, 2002, 2003; Stuart & Phillips, 1997) and in fluctuating maskers (Festen & Plomp, 1990; Van Summers & Molis, 2004). We did not find as big a decrease in performance as speech and noise levels increased from 62 to 82 dBA as Studebaker (1999) did. One explanation for this finding may be that in the present study, word recognition of CVC words in isolation was measured. In the Studebaker (1999) study, the subjects had to recognize words that were in a carrier sentence 'Say the word "…"'. The total duration of the stimulus was longer, which might have had an effect on recognition performance. Furthermore, Studebaker (1999) used bandpass filtered speech, but in the present study, broadband filtered words were used. Thirdly, in the Studebaker (1999) study, word recognition was measured at very high SNRs (SNR -4 to 28 dB). In the present study, SNRs ranging from -12 to 0 dB were measured in steady noise. We found a decreasing effect of higher noise levels on performance in steady noise at higher SNRs (-3 and 0 dB). It is suggested that if higher SNRs are measured in a follow-up study, the decreasing effect will be stronger, especially when measured at even higher noise levels, if possible.
Another finding was that performance increased for broadband and highpass filtered speech with increase in SNR, regardless the competing noise condition. This finding was expected, since a higher SNR means that more speech information is available for word recognition. What was not expected, though, was the big difference in performance that was found between the HP and the LP conditions. The LP conditions are clearly more difficult to recognise than the HP conditions, and we found no greater decreasing effects of high levels on highpass filtered speech compared to lowpass filtered speech. An explanation might be that the pilot study was not extensive enough to find the correct cutoff frequency. It would

require an extensive study to derive the exact cutoff frequency for the NVA word lists that would give equal performance, which would be nice information for future studies with filtered words. Another factor that could have influenced the present results is the speech material that was used. The speaker pronouncing the words of the NVA lists has a very particular speaking style. Some phonemes are over-articulated, such as the /l/ at the end of the word 'doel' or 'koel' or the /r/ at the end of 'door', resulting in some words being recognized more easily than others. An effect of word material was also found by Rhebergen (2006). He measured SRTs with the Plomp sentences (pronounced by the same female speaker as the NVA word list) and did not find an effect of level. However, he did find an effect of level when he used the VU sentence material (Versfeld et al, 2000).

Furthermore, there may be an effect of observer. The subjects repeated the presented material orally and their responses are judged by the experimenter. The test results may therefore also be influenced by a bias of the experimenter being more of less strict in her judgments.

We found a significant learning effect in this study. Statistical analysis revealed that performance scores were significantly higher in the retest. This is in line with findings by Cainer et al. (2007) and Rhebergen et al. (2008b), who also found a general pattern of learning in speech-in-noise discrimination. The material that was used in this study was also susceptible to the learning effect; after the first test, many subjects revealed that they discovered the CVC pattern in the material. To avoid this in future experiments, it may be advisable to use word material that has multiple syllable structures like CV-CVC (for example, words like 'ka-non', 'be-leg'), CVC-CV ('kat-je') or CV-CV ('ma-ma').

8. Conclusions

Based on the results of this study, and other ones in the literature, the following conclusions are reached:

1. Speech recognition performance increases with increases in SNR for all conditions, except for the lowpass filtered words presented in steady noise.

2. In interrupted noise, performance is significantly higher across noise levels 62, 72 and 82 dBA than performance in steady noise for the broadband, highpass and lowpass conditions.

3. There is a significant interaction between SNR and noise level when noise is interrupted. In steady noise at high SNRs (-3 and 0 dB) there is a trend towards a decrease in performance at noise levels higher than 72 dBA.

4. Lowpass filtered speech is more difficult to recognize than highpass filtered speech. Increasing the level of lowpass filtered speech at the same SNR does not improve speech recognition.

Acknowledgments

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Appendix I: Tone and speech audiogram

Patiënt Nr.
Patiënt naam
Geboortedatum
Geslacht
Adres :

Telefoon :

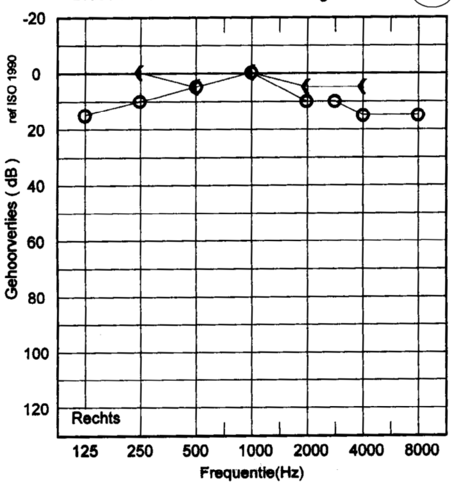
Audiologisch Centrum

Meibergdreef 9, D2
1105 AZ Amsterdam
Telefoon: 020-5663724
Fax: 020-5669068

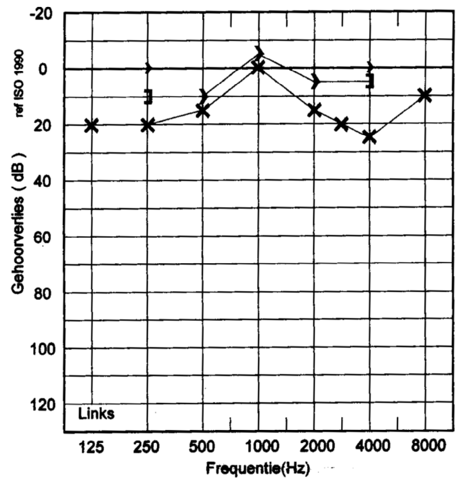
Datum **Audiometer** A1 **Naam onderzoek(st)er** CC

Toonaudiogram 14/09/2009

Brede Fletcher.: 8 dB Lage Fletcher.: 5 dB



Brede Fletcher.: 14 dB Lage Fletcher.: 10 dB



Maskering (dBHL)	Lucht	Been
		25/35, 25/40

Maskering volgens Hood met Band

Legenda

Basis symbolen

	Ongemaskeerd	Gemaskeerd
Lucht geleiding	L × R ○ B ⋈	L □ R △ B ⧗
Been geleiding	L › R ‹ B ⌄	L] R [B ⌴
Vrije veld	L F R F B F	L Γ R Γ B Γ

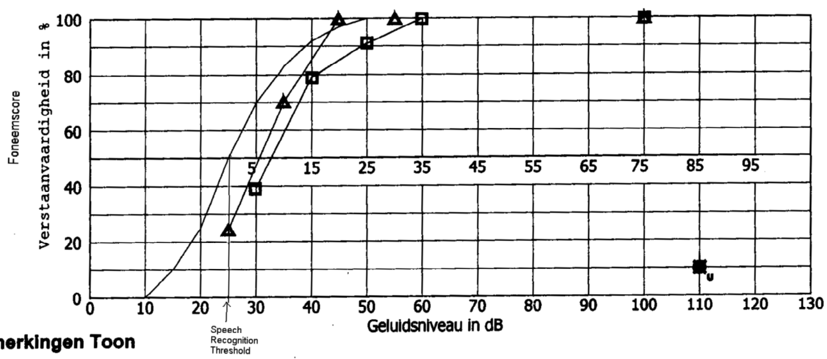
Combinatie symbolen

Warble	W	Pulserend	=
Kinder	↾	Witte ruis	N
Band ruis 1/12	II	Band ruis 1/3	III
Geen resp.	↙↓↘	Beter dan resp.	↑
UCL	U	MCL	M

Kleur codes

Links (L)
Rechts (R)
Binauraal (B)

Spraakaudiogram 14/09/2009



Opmerkingen Toon

Opmerkingen Spraak

Gelicenseerd aan : AMC