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The impact of time delays in hearing aids on the benefit of speechreading.

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- ABSTRACT -

The purpose of this study was to examine the impact of delays on the benefit of speechreading. This was evaluated with a speech perception test, a modified version of the *Just Follow Conversation test (JFC)* in this study called *JFC live*. The speech material was presented live by a woman who read out loud pieces of text. The speech material was presented in competing noise. Twenty-three test subjects participated in the test, twelve men and eleven women. Different delays (0-200 ms) were presented to the test subject during the test. Furthermore, one cognitive function, working memory, was tested with the *Reading Span test* after the *JFC live*. The result showed that hearing impaired people benefited from visual cues. The majority of the test subjects suffered from the tested delays (0-200 ms) but in general not by shorter delays <40 ms which this study aimed to investigate.

Key words: *Just Follow Conversation test*, delays, speechreading, *Reading Span test*, working memory.

- PREFACE -

During the spring term of 2004, I have been working with this master thesis at Eriksholm Research Centre, Oticon A/S, Denmark. To do this study I have relied on help and instructions from several persons working at Eriksholm, especially my two advisors Søren Laugesen and Elisabet Sundewall. I would like to thank these two for supporting me with valuable help, knowledge, and inspiration during this study. Furthermore I would like to thank Jette Damm Lützhøft for neverending patience, reading inspiration and beautiful voice. I am grateful to all of the employees at Eriksholm for their support and engagement and for taking good care of me during there.

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Louise Prytz

“In my youth all the girls talked abot the eye’s of the boys,
I did not understand what they talked about,
I never looked at the eyes, I only looked at the mouth of the boys,
- but at least I did know what their teeth looked like”
/A test subject, hearing impaired since birth

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- INTRODUCTION -

In this chapter, the rationale for the choice of topic for this study is discussed. Furthermore the purpose and delimitations of the study are described.

1.1 Background

Most of our daily communication takes place in background noise, where we can both see and hear the speaker. This introduces the possibility to speechread, for an improved speech understanding. The author's experience is that we are all sensitive to desynchronizations between sound and picture, for instance watching TV with delayed visual input, or where the sound is delayed. This sensitivity should also be present elsewhere, e.g., - in a speech understanding test with audio-visual presentation and delays. The existence of delays in hearing aids, due to complex signal processing, is a fact. Delays in hearing aids can be explained by the time it takes for the amplifier to transfer the incoming signal from the microphone to the opening of the speaker (see figure 1). The delays that are present in digital hearing aids sold on the market today vary between approximately 4-12 milliseconds (ms). More sophisticated new techniques, for a more precise and consistent stimulus encoding and feature extraction may need longer processing times. But the amount of time available for this purpose is limited. Future hearing aids might have digital signal processing which creates longer delays than the ones used today. Most hearing aid producers try to keep the delays as short as possible, probably to give the hearing aid user a close to natural hearing as possible and avoid disturbing effects, on speech perception and speech production.

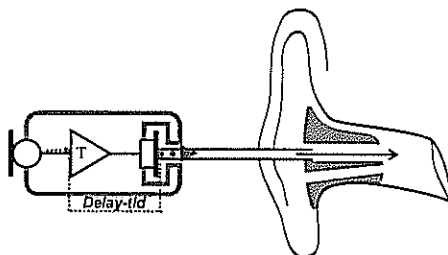


FIGURE 1: A DESCRIPTION OF THE DELAY IN A HEARING AID.

Earlier studies have shown that delays shorter than 40 ms (McGrath & Summerfield, 1985) do not have any negative effect on performance. The impact of delays on the speechreading benefit has not, according to the author's knowledge, been evaluated during the past years. The existing studies concerning these two factors have mainly tested long delays. In 1999 Stone and Moore tested shorter delays, 6 to 40 ms only auditorily, on normal hearing people who received a simulated hearing loss. Since we probably all are sensitive to delays, it is interesting to further study and evaluate the impact of short delays on speechreading.

1.2 Hypotheses

A basic assumption for this study is that the presence of visual cues results in an increased speech understanding. This has been shown in earlier studies, such as Middelweerd and Plomp (1987). In order to test whether this assumption is valid the first hypothesis is:

Hypothesis 1: People with hearing losses benefit from speechreading.

It might be the case that hearing impaired people utilise visual cues to a greater extent than normal hearing people do. This holds true even though the hearing loss is compensated for with hearing aids, since the hearing aid can not compensate for the reduced spectral and temporal resolution in the cochlea. Erber (1975) found that as the hearing loss increased, the higher the benefit of the visual contributions became.

Hypothesis 2: A greater hearing loss results in a greater benefit of speechreading.

Working memory is one of the information processing components involved in speechreading. The working memory stores parts of the message during ongoing processing. The storage is temporary and lasts until the decoding and filling in of the missing parts of the message are possible. In this study the *Reading Span test* (Daneman & Carpenter, 1980) was used for evaluating if there was a correlation between cognitive function (i.e. working memory) and skill in speechreading and sensitivity to delays. According to Lyxell and Rönnberg (1993), speechreading performance in background noise is critically related to the individuals' working memory capacity. The working memory is an essential requirement for speechreading, and the speechreading performance might be predicted from the *Reading Span test* (Lidestam et al. 1999). The *Reading Span test* tests the storage and processing component of the short term memory.

Hypothesis 3: A well developed working memory results in a greater benefit of speechreading.

As the asynchrony between the auditory and the visual input increases, the benefit of the visual input decreases and thereby the possibility to speechread.

Hypothesis 4: An increased delay decreases the benefit of speechreading.

1.3 Purpose

The purpose of this study is to test the hypotheses listed above.

1.4 Scope

This study focuses on the perception of delayed speech introduced by hearing aids. The relation between delays and speech production is not investigated. This limitation is only due to lack of time, and would be interesting to study in the future.

Chapter 2.3 only briefly discusses cognitive functions. It is an interesting issue if cognitive functions (working memory) have an influence on the skill of speechreading. The purpose is to give the reader a short orientation about the possible impact that cognitive functions have on speechreading, and to evaluate if a correlation between the benefit of speechreading and working memory can be found.

- THEORY -

In this chapter, the theories about speechreading, speech perception, delays and cognitive functions are described. The content of this chapter is mainly based on previous findings in these areas.

2.1 Speechreading

Speechreading has been defined as “the ability to understand a speaker’s thoughts by watching the movements of the face and body and using information provided by the situation and the language” (Kaplan, 1997, p.1). After an exposure to auditory and visual signals, the cochlea and retina arrange the incoming signals. The signals thereafter proceed on to the brain, where they are decoded. The signals from the cochlea and retina are summed up, and the result is what has been seen and heard. By using the two different signals, it is possible to complete and fill in the parts that might have been missed by the ear or eye alone, according to Houston and Montgomery (1997). Speech perception varies in three ways: auditory, visual, and auditory and visual in combination (audio-visual) according to Lidestam et al. (2001). In face-to-face situations, information is available to the listener in audio-visual form. All three of the possible ways can be used to comprehend speech, but the most common ones are auditory and audio-visual. This is due to the fact that visual speechreading is demanding on the speechreader’s capacity to fill in missing information. According to Lidestam et al. (2001), audio-visual speech contains more information than auditory and visual speech separately. The two latter complement each other. Rönnerberg et al. (1996) found, almost needless to say, that audio-visual speechreading supported by context and typical sentences generate the best performance. This is, however, only valid if the listener can integrate the information that the two sources contain (Grant & Seitz, 1998). For both people with normal hearing and hearing impairment, speechreading is an essential complement when the auditory signal is unclear (Lonka, 1995), and is frequently used and relied on in speech understanding (Lansing and McConkie, 1994).

The presence of noise and reverberation may make it difficult to hear what is being said in listening situations. In these situations, the possibility to speechread might be the decisive factor for understanding an auditory message or not (Grant & Seitz, 2000). A majority of the observers find speechreading helpful in understanding a message during unsatisfying listening conditions according to Summerfield (1987). Facial expressions contain information and are therefore important in speechreading. Lidestam et al. (1999) found that displayed emotions significantly improved speechreading performance tested on people with normal hearing. This finding was true for both sentence based speechreading and word decoding. "The better a speechreader can interpret body language and facial expressions, the better the understanding of the message" (Kaplan, 1997, p. 129). However, Kaplan remarks that even though speechreading is a valuable complement to listening, it cannot serve, on its own, as a substitute for listening.

2.1.1 Obstacles to speechreading

Factors that can have a negative influence on speechreading are for example: unique and unclear lip movements, uncorrelated body movements, objects in the mouth or facial hair. Furthermore, a long distance between speaker and listener, group conversations and bad lightening on the speaker's face can have a negative impact on the ability to speechread. If presented with inaccurate visual information that creates a discrepancy between the auditory and the visual information, a person might be misled, according to Reisberg et al. (1987). This is the case even though the subjects are aware of the fact that the visual information is irrelevant.

Further the so-called "McGurk effect", was established from the results of a study by McGurk and MacDonald (1976) where the subject was presented with information that was conflicting (i.e. two different phonemes) but were temporally matched. A woman presented an utterance of the syllable [ba] which had been dubbed on to lip movements for [ga]. The test subject reported that [da] was heard. When the visual input was excluded the test subjects reported the correct syllables [ba] or [ga]. Some other obstacles to speechreading are, according to Kaplan (1997), a lack of knowledge about the language used, the use of language redundancies, the ability to pick cues from the surroundings, and a general knowledge about communication strategies.

2.1.2 Speechreading and hearing loss

The presence of a hearing loss often results in the learning of new communication supplements, such as speechreading. According to Hygge et al. (1992), how much the supplement is used, depends on the degree of the hearing loss. Erber (1975) found that as the hearing loss increased, the higher the benefit of the visual contributions became. The magnitude of the contribution was defined as the

difference between the audio-visual and auditory scores. Rosen and Corcoran (1982) state that people with severe hearing losses and wearers of hearing aids, tend to use their hearing aid more as a tool for increasing their ability to speechread rather than as a tool for increasing the hearing ability. An increased age and impaired hearing often results in a higher reliance on speechreading (Summerfield, 1987), but speechreading can be difficult to apply due to the different factors discussed in the previous paragraph (2.1.1).

Tillberg et al. (1996) found a relationship between the duration of hearing impairment and the ability to utilise visual cues. A longer duration of hearing loss, resulted in better visual performance, i.e. greater benefit of visual cues. This supports Ludvigsen's (1981) finding, that people with a congenital hearing loss benefited more from visual cues than hearing impaired people with an acquired hearing loss. Furthermore, Tillberg et al. (1996) found a correlation between the degree of hearing loss and the performance on auditory and visual tests. The more severe the hearing loss, the poorer performance in auditory tests but better performance in visual tests. Several studies (Rönnberg et al., (1983), Hygge et al., (1992), Lyxell and Rönnberg, (1989) and Lyxell and Rönnberg, (1991)) have shown that there is no difference in utilising speechreading between normal hearing and hearing impaired people.

2.1.3 Positive influence of visual cues in noise

The primary information in speechreading is collected from the place of articulation, i.e. how the lips are shaped during speech (Walden et al., 2001). The amplification in hearing aids supplies information about the place and manner of articulation plus voicing information (Walden et al., 2001). In languages, pieces that carry meaning to the message exist, which are not accessible through speechreading. Kaplan (1997) gives the following examples: stress, intonation, and some of the vowels and consonants. Ross (1998) found that of all speech sounds in the English language, only about 30 % are possible to speechread, i.e. clearly seen on the lips. The remaining sounds are produced inside the mouth and are thus not visible to the speechreader.

Summy and Pollack (1954) found that if the listener in a speech perception test could see the face of the speaker, the signal-to-noise ratio was improved by 15 dB. The speech material used was bisyllabic words. The text material was presented by a live speaker, and the noise derived from a gas tube source electrically mixed with the speech signal. Hawkins et al. (1988) tested two groups: normal and hearing impaired test subjects in a speech perception test. The speech material was continuous text presented audio-visually or auditorily only. The competing noise was multitalker babble. In the test two subjective criteria were used; a) subjects were instructed to set the background noise where they could "understand 50 % of what was being said"; b) "just follow conversation". A comparison between the two groups showed that the group with the hearing impaired subjects needed 4-5 dB higher SNR's to get a performance at the same

level as the group of normal hearing people, both with and without visual cues. According to Hawkins et al. (1988) the presence of visual input improved performance (5-6 dB) for the two groups when either one of the two subjective criteria was used.

The contribution of speechreading to speech perception was evaluated by Middelweerd and Plomp (1987) based on young test subjects with normal hearing, and elderly test subjects with presbycusis but without hearing aids. The threshold of sentences in noise was defined as 50 % correct syllables. When the visual input was added to the auditory input, the young test subjects showed an improved result of a 4.6 dB lower threshold, and the elderly test subjects 4.0 dB. The contribution of visual cues in a speech recognition test was also tested on people with normal hearing by MacLeod and Summerfield (1987). The test was obtained audio-visually. The presence of visual cues, presented in a background noise at a level of 60 dBA delivered a benefit of 11 dB. This result implied that also people with normal hearing benefit from visual cues and the authors' conclusion was that hearing impaired people were not better in utilising visual cues compared to people with normal hearing. New results concerning the benefit of visual cues was found by MacLeod and Summerfield (1990) where the results showed a benefit of 6.4 dB, for normal hearing people. This result is, according to MacLeod and Summerfield in agreement with earlier findings (Plomp, 1978), i.e. the addition of speechreading leads to an improvement of 5 to 8 dB. McCormick (1980) found an interesting result, when measuring the intelligibility of sentences presented in noise, auditorily alone and audio-visually. The results showed a correlation between the scores obtained in the auditory-alone presentation and the benefit of the audio-visual presentation. The poorer the scores received in the auditorily alone presentation, the greater the audio-visual benefit.

Hygge et al. (1992) studied the performance of test subjects on a *Just Follow Conversation test*¹, with different competing background noises. The three different types of noise examined were speech-spectrum random noise, a male voice and a male voice played in reverse. Both normal hearing and hearing impaired test subjects participated in the study. Fifty percent of the trials were presented audio-visually and the remaining fifty percent with sound only. In a third of the trials speech-spectrum random noise was presented as background noise. Another third trial was presented against a male reading a text, and the final third was presented with a background noise, which consisted of the same male voice which was played in reverse. The speech material was audio-video recordings and was presented to the test subject on a screen and through a loudspeaker. Hygge et al. found a difference in performance between the normal and hearing impaired test subjects, where the normal hearing test subjects performed better against a background of speech (forward or reversed), compared to when exposed to steady-state noise. Speech-like noise released the effect of masking for the normal hearing test subjects, but not for the hearing impaired test subjects. This is probably because of their reduced temporal resolution of auditory stimuli. Another possibility could be that the hearing subjects were better at separating different speech sources due to their overall better hearing (A.

¹ See chapter 3.2

Löfqvist, personal communication, June 7th, 2004). By this reduction the hearing impaired receives less benefit from the variations of amplitude in natural speech (Arlinger & Gustafsson, 1994). Forward speech did not mask more than reversed speech did, which was one author's initial belief. Furthermore, Hygge et al. found "a major effect of a reduced amount of masking from background speech than from noise". The contribution of speechreading received from audio-visual presentation relative to auditory presentation did not differ between the two groups. The authors state that this result is consistent with the theory from Lyxell and Rönnberg (1989) where the compensatory use of visual cues of speechreading does not spontaneously develop with a hearing impairment.

The benefit received from visual input to auditory speech perception has traditionally been measured as the difference in the percentage of correct answers between the auditory presentation and the audio-visual presentation, according to MacLeod and Summerfield (1990). This difference does not however, provide a precise measure of how large the benefit is. The reason is that the relation between the benefit and the speech-reception ability is not linear, and does not constitute an interval scale of measurement. Since the scale of percentage correct is bounded at zero and one hundred percent, the change in performance of the test subject is limited. Therefore it is not reasonable to compare the size of changes in performance, according to MacLeod and Summerfield (1990). The *JFC test*, the *JFC live*², might provide a better measurement of the benefit since the result is presented in signal to noise ratio (SNR).

2.1.4 The effect of training in speechreading

Dodd et al. (1989) state that speechreading skills can be significantly improved, whereas sceptics, not named by Lonka (1995), claim that good speechreaders are born, not made. Tye-Murray (1992) implies that speechreading performance is not improved unless the training is based on a "situation-related anticipatory strategy", i.e. the training must not be focused on the learning of new words and phrases. However, both Lonka (1995) and Dodd et al. (1989) showed results of improvement in speechreading for test subjects after training. The improvement was about 13-14% after five weeks of practice. The test subjects in Lonka's study, who all had hearing losses ranging from moderate to severe, were provided with a video tape where different speechreading exercises were recorded. One of the groups studied at home, one in class, and one control group did not study at all. The results did not differ between the students who studied at home or in class; they all improved compared to the control group. The lip-readers with an initially poor performance showed a greater improvement than those who already had good speechreading capability. Sex and age did not have any influence on the improvement.

² The name of the modified JFC version used in this study.

Other studies have also shown results of improvement after training, with the amount of improvement, expressed in percentage, ranging from 10% (Oyer, 1961) to 50% (Sims, 1978). These large differences can be explained by differences in the choice of test subjects, the duration of the training period, and the test materials used. Rönnberg (2003) implies that a superior skill will not develop spontaneously despite a daily exposure to or demand on visual communication.

2.2 The influence of delays on speech perception

Today, digital signal processing is the predominant type of signal processing in hearing aids, and this processing result in delays ranging from a few milliseconds up to tens of milliseconds, depending on the kind of hearing aid. The delay originates in between the microphone and the receiver in the hearing aid, and is partly produced by the analogue-to-digital and digital-to-analogue converter. In hearing aids with analogue signal processing, the delay is less than one ms. The presence of delays, mainly large ones, can cause difficulties for the listener such as: seeing the lips move and hearing the sound later, disrupted speech understanding, perceived echo and affected speech such as stuttering (Agnew and Thornton, 2000).

An early study about the interaction between delays and speech understanding was made by König (1965). Both isolated words and sentences were used as stimulus material, and a specially designed apparatus (a magnetic drum with multiple recording and playback heads) was also used in the test. Only one test subject was tested, and the result was that the test subject was not able to detect delays shorter than 240 ms. It was not until the delay exceeded 240 ms that speechreading was disturbed. It has later been proved by researchers that even though a delay is not detectable, the asynchrony between auditory and visual input might still have a negative influence on speech understanding (Pandey et al., 1986).

McGrath and Summerfield (1985) tested the performance of normal hearing people on an auditory and visual identification test. The auditory signal was replaced with series of rectangular pulses derived from a laryngograph and thereby coordinated to the closing of the speaker's vocal folds, corresponding to the F0 of the voice. When the auditory input was delayed by 160 ms, the identification scores were not better than when the condition was video only. Other examined delays (20, 40, and 80 ms) resulted in better results than the auditory presentation alone. Campbell and Dodd (1980) found the same effect; even if the test subjects showed poorer result in the speech perception test with delays of 400, 800 and 1600 ms, they still performed better when the two inputs were time shifted, compared to the auditory only condition. The results from the study of McGrath and Summerfield (1985) showed, for the group as a whole, that delays up to 80 ms had a modest effect on the group-mean performance. None of the three delays showed any significant decrease of the performance when the

scores were compared to the zero delay. McGrath and Summerfield (1985) divided the whole group into subgroups based on the test subjects' speechreading ability. This classification showed that the group with better speechreaders had significantly poorer results with increased delays, ranging from 0-80 ms. The conclusion of McGrath and Summerfield was that delays up to 80 ms, produced by signal processing, might be acceptable without having any significant effect on auditory and visual perception of speech. A small but statistically declining performance for delays ranging from 20-160 ms was found for subjects with good speechreading ability, but the average group and the poor speechreaders showed insensitivity to delays shorter than 80 ms. The two authors stated that 40 ms might be a safer estimation on how large a delay can be before it starts affecting speech understanding.

Pandey et al. (1986) studied the effect of delayed auditory signal on audio-visual perception of videotaped sentence lists which were videotaped, with and without a picture. The picture worked as a context and represented one of the key words in each sentence. This was tested monaurally on twelve test subjects with normal hearing. The delays used were 0, 60, 120, 180, 240 and 300 ms, and the speech signals were presented at 0 or -10 dB SNR. The noise consisted of a multitalker babble at a constant level of 60 dBA. The video signal was presented on a TV monitor. The result showed that, despite the fact that none of the test subjects with normal hearing had had any training in speechreading, they benefited from audio-visual input. Compared to the 0 delay the test subjects did not show any deterioration of the scores for the delays up to 240 ms. In all delays, the audio-visual scores were better than the scores received in the visual or auditory respectively. The SNR of -10 dB showed more pronounced effects of disruption caused by delay compared to the SNR of 0 dB. When the delay was 300 ms the audio-visual scores were no better than the ones in the visual condition. With such a long delay, the advantages of the auditory signal disappear, according to Pandey et al.

A second test was performed by Pandey et al. which tested six skilled speechreaders with normal hearing with the same method. In this test the delays of 0, 80, 160 and 240 ms were tested at a SNR of -5 dB. Pandey et al. concluded that below 80 ms, the effect of delay is not significant; and this result confirms the finding by McGrath and Summerfield (1985) where the sensitivity to audio-visual asynchrony is not notably disturbing for phonemic identification in connected speech, but the effect becomes significant at a syllabic level. Furthermore, Pandey et al. found that moderate delays, shorter than 80 ms introduced in signal processing, would not interfere with the benefits received from the auditory signal for audio-visual perception of connected speech. These results should, according to the authors, only be considered as a guideline since they were based on twelve people with normal hearing and the auditory signal used in the test differed from the one received through a hearing aid.

Stone and Moore (1999) tested the impact of short delays 6-40 ms on normal hearing test subjects, to investigate how the effect of the delay varied as a function of hearing loss. The test subjects received simulated hearing aids and

simulated hearing losses. The recorded speech material was only presented auditorily. The test subjects were informed about the delays and their task was to rate the different delays on a scale of different degrees of perceived disturbance. The results showed a relation between the degree of hearing loss and the disturbance of the delay. The disturbance increased as the delay increased. Delays of 20 to 30 ms were reported, by the test subjects, as disturbing with simulated losses corresponding to mild and moderate. Stone and Moore suggested that for people with hearing losses at low frequencies, moderate to severe, delays up to 40 ms might be acceptable. In a later study by Stone and Moore (2002), it was found that the type of room and the acoustics inside the room have influence on the perception of and coping with delays. In a “dry” environment, i.e. a double-walled booth, the perception of speech is disturbed at 15 ms, compared to 20 ms in a “live” environment, i.e. an office according to Stone and Moore (2002).

2.3 Cognitive function – working memory

A workspace used while thinking, where visual and auditory input at the same time are processed and stored, is referred to as working memory by Baddeley, (1986). The idea of working memory also refers to a short-term memory system (Lyxell & Rönnberg, 1989). According to Cowan (1998), working memory is a number of mental processes, in which information is stored temporarily in order to serve in mental computations, and is kept as long as the person is attending. A person with a well developed ability to fill in missing parts of a message probably has a large working memory capacity, and this capacity makes it possible to store and process information for a short period of time (Lyxell et al., 2003). Pichora-Fuller et al (1995) state that speech understanding is dependent of a well functioning working memory, since this temporary storage is responsible for both processing and storing during performance in cognitive tasks. By this previously explained function of working memory, memory span tests like the *Reading Span test*³ would theoretically, according to Lyxell & Rönnberg (1989), be considered as a relatively easy measure of working memory, because it mainly taxes only one component, the storage component “of a more complex information-processing system”(Daneman & Greene, 1986; Dixon et al. 1988). The *Reading Span test* puts high demand on the working memory, since it is a dual task (Hällgren et al. (2001a) and Lyxell and Rönnberg (1993)). The concept of dual task means that processing and storage occur at the same time (for further details see 3.4.5).

Hällgren et al. (2001a) found a negative correlation between age and cognitive performance. This was also found by Lunner (2003), who tested a population of hearing aid users with ages ranging from 33-89. For hearing impaired elderly this decrease is even more critical than for elderly with normal hearing. This is due to the fact that a hearing loss is more demanding on the cognitive capacities, according to Pichora-Fuller et al. (1995). Furthermore, Lunner found that greater HTLs (Hearing Threshold Levels) corresponded to poorer speech recognition in

³ For an overview see paragraph 3.4.5.

noise. A correlation was found between the results of the *Reading Span test* and the SNRs obtained in noise. This indicated that low SNRs in noise are associated with a large working memory capacity according to Lunner (2003). This was tested on the population both with and without hearing aids. As a conclusion of these findings, Lunner (2003) stated that to perform well in noisy listening situations, a well developed cognitive function is essential, either with or without a hearing aid. When young and elderly people with similar audiograms were compared, The Committee of Hearing Bioacoustics and Biomechanics (1988) found that the elderly showed a decreased amount of working memory accessible for speech understanding. The decreased ability might be explained by age related changes in the auditory process, for instance presbycusis (Pichora-Fuller et al., 1995) or it might be a result of a deterioration deriving from the cognitive processing of speech. A combination of the two might also be the reason, according to Pichora-Fuller et al. (1995). These two possible explanations for the decreased working memory capacity might also serve as possible explanations to the fact that elderly people experience difficulties in understanding speech in the presence of noise. When a signal is degraded due to noise, a greater degree of resources is needed; and the working memory is faced with a high demand in order to store the information, process it and understand it during a short period of time, according to Hällgren et al. (2001b).

To summarize it: most cognitive processing models assume that resources are limited, and thus that if more resources are allocated to a given process, less resources are available for other processes. This means, that when the acoustic/auditory information is degraded, more resources are required for the extraction of this information, and thus less resources are available for other processes, be they working memory, lexical search and access, or semantic/syntactic processing. (A. Löfqvist, personal communication, July 6th, 2004).

2.3.1 Skill in speechreading

Working memory is one of the information processing components which are involved in speechreading. According to Lidestam et al. (1999), working memory is an essential requirement for speechreading. Lyxell et al. (2003) found a positive correlation between the size of the working memory and the success of using communicative and conversational strategies. Lyxell and Rönnberg (1993) consider that the capacity of the working memory probably constitutes one "critical information-processing component" in speechreading, because not all speech sounds are visible to the speechreader on the speaker's lips. It is relevant to presume that the speechreader stores parts of the information from the message. The storage is temporary and exists just until the decoding and the filling in of the missing parts of the message is possible (Lyxell and Rönnberg, 1993). Rönnberg et al. (1996) suggested three different predictors for the skill in speechreading. The first one is the decoding ability and the information-processing speed. This predictor is, according to the authors, important for the population in general, but

especially for the elderly taking advantage of speechreading. The second one, verbal inference-making/guessing, constitutes an indirect back-up system and is usable and important when the context is poor. The third one, suggested by Rönnberg et al. is working memory capacity. This is important when processing demands are high, or when a superior speechreading skill has been developed.

Speechreading performance might be predicted from the *Reading Span test*, according to Lidestam et al. (1999). Rönnberg et al. (1999) reported, from a comparative study between an extremely talented speechreader and a control group that a relation between high cognitive capacity (working memory) and speechreading skill exists. No difference was found to confirm that a hearing loss would affect the working memory capacity negatively, according to Lyxell et al. (2003). However, it is quite well established that a hearing loss, especially that of cochlear origin, imposes high demands on the cognitive skills and less is left to the main task – listening (Pichora-Fuller et al., 1995).

A number of information processing skills are, according to Lyxell and Rönnberg (1989), Lyxell and Rönnberg (1987) important for speechreading. These are: 1) the ability to decode the words that appear on the lips of the speaker, 2) the speed in processing and accessing lexical information from the long-term memory, 3) the guessing and inference making ability in sentence completion tasks under pressure of time. Lyxell et al. (1996) found a relationship between the skill of interpreting facial expressions and the speechreading skill. Non-verbal information, such as facial expressions, becomes less important when the verbal message contains enough information to facilitate information processing. Messages that contain a low level of verbal information show the opposite. According to Lyxell et al. (1996), facial expressions are a part of a checking procedure, where the expression is matched with the verbal content of the message.

3

- METHOD -

In the following chapter the method of the pilot study and the main experiment are presented. The description of the Just Follow Conversation test precedes the pilot test and the main experiment. The chapter ends with a presentation of the Reading Span test.

3.1 Initial Considerations

The studies that have been presented in the previous chapter (2.2) differ from the test (*JFC live*) used in this study. Previous studies, in which the impact of delays has been investigated have mainly tested long delays >40 ms. In the studies where shorter delays have been tested, the presentation has been auditory only; and the studies have mainly focused on when delays could be detected, and not on decreased speech understanding like in the *JFC live*. In this study the test subjects are hearing impaired people, which also differ from some of the previous studies. The use of a live speaker⁴ also differs from most of the described studies, where the speech material has been recorded speech, presented on a TV screen. No test like the *JFC live* has, according to the knowledge of the author, been published where: 1) the test method used is the *JFC test*, 2) a live speaker who presents the speech material is used, 3) audio-visual and auditory presentation is used, 4) mainly short delays are tested, 5) the test subjects are hearing impaired, 6) the focus is on speech perception, 7) the critical delay is estimated based on the delay where the speech understanding starts to decrease.

Speech intelligibility can be obtained objectively or subjectively. In the former, the result is often expressed in percentage of correct words, completed sentences or as a replication of phonemes or sentences (for an overview see Hagerman (1984)). The choice of a live speaker for presentation of the speech material was an attempt to create a natural and realistic listening situation, where the possibility to speechread was close to optimal. The use of video-recorded speech material would have provided several disadvantages to this test. First, the main purpose of this study was to study the effect of short delays (i.e. shorter than 40 ms). The use of a video-recorder and recorded speech results in a less good synchronisation. The time it takes for the picture to be built up (40 ms) results in a

⁴ A real person presenting the speech material

desynchronization between the speech and picture, which is in the range of the delays of interest. The speech intelligibility test most used today in Danish clinics is Dantale. This speech intelligibility test originally consisted of recorded speech, which was presented auditory only. Fifteen years ago the speech material was complemented with a video recording of the woman who presented the speech material. This test with the audio-visual presentation was considered to be used in this study, but it showed disadvantages that would result in that the main purpose, i.e. to investigate the impact of short delays, could not be fulfilled.

3.2 Just Follow Conversation test

The *Just Follow Conversation (JFC) test* was designed in the end of the 1940's by Hawkins and Stevens (1950). The baseline version of the *JFC test* used for this study is the Eriksholm Version, Oticon A/S Research Centre, which was implemented in the summer of 2000. The *JFC test* aims to test speech intelligibility in competing noise. One of the differences between *JFC* and other conventional speech intelligibility tests is the use of running speech, i.e. not isolated words or sentences. This gives a more life-like and realistic listening situation. The test subject is active and participates by means of adjusting the noise level, in other words, finding the right relation between speech and noise until it is possible to understand most of the text, thereby the name just follow conversation. This level might result in that a few words are lost, but the context of the text is understood. When the test subject is satisfied with the adjusted noise level, according to the conditions above, she/he pushes the adjustment knob, and the signal-to-noise ratio (SNR) is calculated. Thus, the result, or answer, depends on a subjective judgement from the test subject. Studies by Neumann & Søggaard Jensen (2000) show that the level where the test subject just can follow conversation is stable, and the intra-individual standard deviation (stdv) for the *JFC test* is 1.7 dB. This means that even if the *JFC test* is highly subjective, the reliability is high. The use of such a strict subjective criterion as the one used in the *JFC test* is not odd when compared to daily listening situations. The baseline version of the *JFC test* used for this study showed a standard deviation of 1.5 dB for uncompressed speech material, and 1.0 dB for compressed speech material, both obtained at a noise level of 70 dB SPL. Like Larsby and Arlinger (1994) state, most listeners in unfavourable listening situations unconsciously apply this criterion, by moving closer to the source until it is possible to follow what is being said, and thereby "adjusting" the relation between the signal and the noise. In traditional speech intelligibility tests, the result is calculated by the number of correct answers, given in percent. The latter measure is blunted and difficult to compare with an improvement or deterioration (is an improvement from 40 to 50 percent as good as an improvement from 80 to 90 percent?), according to Houston and Montgomery (1997), and they therefore recommend that a better measure of the result would be to what extent the test subject can resist noise, expressed as SNR in decibel. With this in mind the *JFC test* is suitable for this study, since the result is given as the median of the SNR, and a changed SNR indicates an improved or deteriorated performance. However, in the *Just Follow Conversation*

test no assessment is done of the test subject's actual understanding of the text content (Neumann & Søgaard Jensen, 2000).

Calibration was performed on all of the technical equipment. The speech level was set to represent about 68-69 dB SPL. This level was chosen since it represents a comfortable reading level at the position of the microphone. The use of uncompressed speech in form of a live speaker makes it harder to obtain a constant speech level. In this study, a level meter was presented to the speaker in an attempt to control the level of the speech. The level meter was placed just below the text on the computer screen (DELL, Opti Plex GX110) (figure 2). The level meter was set to mark the target speech level with different colour bars. Each bar was set to represent 1.5 dB. The speaker was instructed to read at a level which was marked with green and yellow bars. As soon as the level of the speaker's voice rose above the target level, the bars above the yellow ones turned red. If the level of the voice was too low the yellow bars disappeared, and only green bars remained.

The baseline delay, due to the difference in the distance from the speaker to the microphone and to the earphones, was calculated to be 1.75 ms, and was compensated for. The reason for compensating for this delay was to imitate the reality for a hearing impaired listener with analogue hearing aids (which does not create any delays). The arrangement of the test can be seen in the block diagram in figure 3.

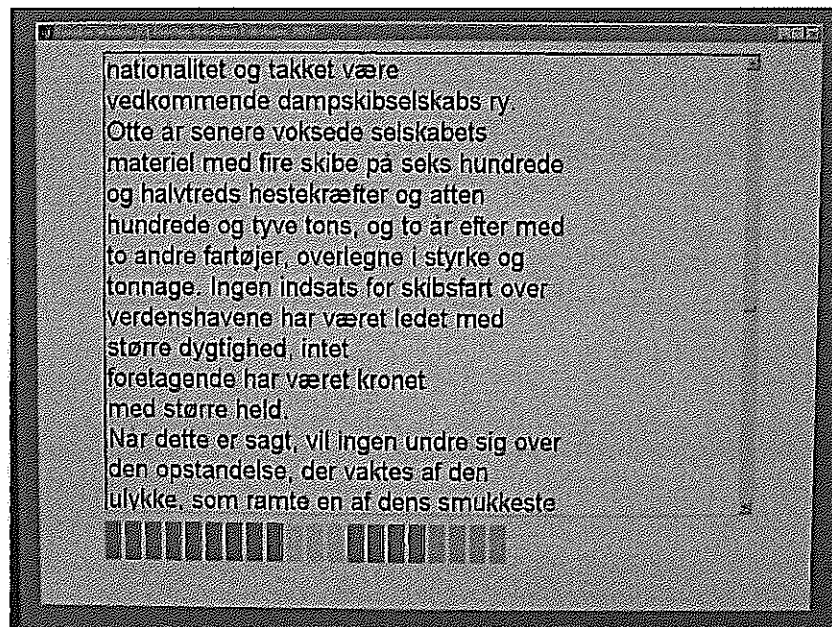


FIGURE 2: THE COMPUTER SCREEN IN FRONT OF THE SPEAKER WITH THE TEXT, AND THE LEVEL METER.

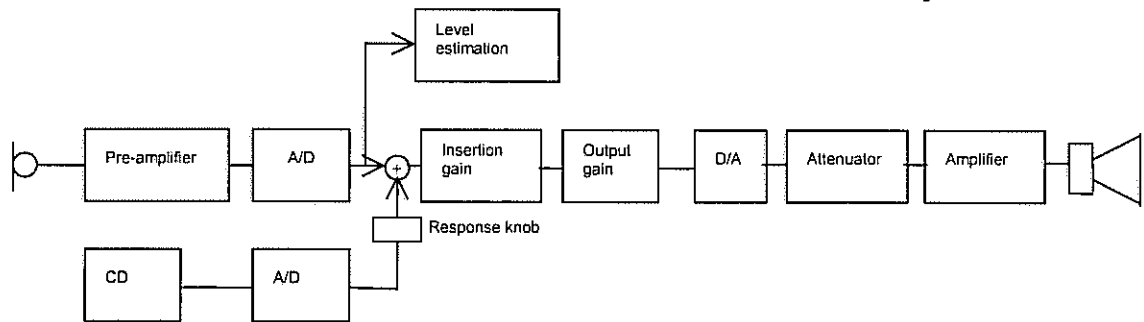


FIGURE 3: BLOCK DIAGRAM OF THE JFC LIVE TEST.

3.3 Pilot Test

3.3.1 Purpose

The objective of the pilot test was to obtain normative data of the *Just Follow Conversation test* with a live presentation of the speech material delivered by a live speaker. The pilot test also aimed to test one moderate delay (40 ms) on a small population of normal hearing test subjects, with ages ranging from 29 to 64 years. The data obtained from the pilot test would then be compared to the Eriksholm version (Neumann & Søggaard Jensen, 2000) of the *JFC test*, showing a standard deviation of 1.0 dB obtained from a population of twenty normal hearing people. The recorded speech material used in the Eriksholm version consisted of compressed speech, presented at 70 dB SPL. If the modified version, *JFC live*, with unrecorded and uncompressed speech could reproduce the above mentioned standard deviation, it would indicate that the use of a live speaker did not affect the results in a negative way, and the *JFC live* was valid.

3.3.2 Test Subjects

The data received in the pilot test originated from 11 people with normal hearing (10 men and 1 woman). The hearing criterion in the pilot test for the test subjects was a pure tone threshold no worse than 20 dB HL at 0.5, 1, 2 and 4 kHz. All of the test subjects were employees, working at Eriksholm Research Centre, Oticon, and participated on a voluntary basis without payment.

3.3.3 Live Speaker and Speech Material

The speech material in this study was presented by a live speaker. The same speaker participated in both the pilot test and the main experiment. The speech material consisted of extracts from 'En verdensomsejling under havet', by Jules Verne, published as an e-book on the internet (www.hernov.dk/ebog). The text material used was in Danish and was revised so that all dialogues, pictures and unusual names or places were skipped. Pieces of the text from different chapters were put together in an attempt to give the text a partly incoherent content. The purpose of the incoherency was to avoid that the listener was caught by the story and forgot about the main task. The speed of the text presentation was chosen, in consent with the speaker, to be in accordance with the speaker's reading speed for this particular text material. It is presumed that the chosen speed is comparable to a normal average reading speed, 80-100 word/minute. According to Byers and Liberman (1959), the speech rate does not seem to have an impact of the speechreading ability. In order to create a constant reading speed, the text was presented in equal steps on the computer screen, and every 2.5 seconds three new text lines were presented.

The noise used in the test was unmodulated stationary noise with the same spectral distribution as speech. The use of this noise proved to give small standard deviations in the results of the test subjects.

The live speaker used in the test was a woman, and the speech material was presented with a clear yet natural voice without theatrical influence. The speaker was seated under lights, overhead lights provided by soft light and by spot lights from both sides at eye level. The speaker, the test subject and the test operator were inside the test room during the test. The test room consisted of a small office (approx. 8m²) with a thick carpet on the floor and a small window with curtains. The speaker was placed in front of a plain blue piece of fabric in an effort to reduce reflections from the light, which could cause unwanted shadows on the face of the speaker. The fabric, which covered two walls from the floor to the ceiling, also served as a sound absorber.

3.3.4 Procedure

In the pilot study, three different conditions were tested. The first one was audio-visual presentation with 0 ms of delay (AplusV0delay), see figure 4. The second condition was audio-visual presentation with 40 ms delay (AplusV40delay). The third and last condition was auditory input with only 0 ms delay (AminusV0delay), see figure 5. The task of the test subjects was to adjust the noise level, i.e. to find the level, or the relation between speech and noise where they were able to follow the presented speech material. The level was adjusted six times for each of the two first conditions. Under the third condition (AminusV0delay), the level was adjusted ten times. The level of the speech was

constant during the test and thereby it was the level of the noise that was adjusted by the test subjects. After each press on the adjustment knob, the level of the noise was automatically reduced and the task of the test subject was to readjust it and find the level where it was possible to follow the conversation again.



FIGURE 4: SPEAKER AND TEST SUBJECT, AUDIO-VISUAL PRESENTATION (A PLUS V).



FIGURE 5: SPEAKER AND TEST SUBJECT, AUDITORY ONLY PRESENTATION (A MINUS V).

3.3.5 Result

The results of the pilot study are compiled in table 1 and showed a group standard deviation of 1.0 dB, obtained from the AminusV0delay condition. The condition of auditory only (AminusV0delay) was compared to the condition with compressed speech, presented at 70 dB SPL in the Eriksholm version. The comparison of these two values was done since the Eriksholm version was tested without any visual input. Since the *JFC live* reproduced the low standard deviation of 1.0 dB, the use of a live presentation in form of a live speaker was

found to be valid and reliable. The results from the pilot test showed that the test subjects did not show decreased performance, (i.e. a higher or worsened SNR) for the delay of 40 ms (AplusV40delay). Ten of eleven test subjects showed a worsened SNR in the auditory only condition (AminusV0delay), compared to the audio-visual condition. The benefit of speechreading was on average 2.05 dB. The benefit was calculated on the result of the AplusV0delay minus the AminusV0delay. The purpose of the pilot study was to evaluate the use of a live speaker. The results showed that this was possible and thereby the *JFC live* could be used in the main experiment.

TABLE 1: RESULTS FROM THE PILOT TEST – NORMATIVE DATA

Subject	AplusV0delay		AplusV40delay		AminusV0delay	
	Median SNR	Stdv dB	Median SNR	Stdv dB	Median SNR	Stdv dB
1	3.2	1.4	2.7	0.4	0.8	0.6
2	-1.4	1.3	-0.8	1.1	0.4	1.0
3	-2.4	0.6	-2.8	1.7	-2.1	0.8
4	-1.5	1.6	-2.3	0.5	-0.9	0.8
5	-2.4	1.0	-2.4	1.0	-1.0	1.5
6	-1.5	0.7	-1.5	0.6	-0.0	0.8
7	-2.0	0.9	-2.8	0.5	0.7	0.7
8	-3.9	1.0	-2.4	0.8	-1.5	0.5
9	-8.7	0.7	-8.0	1.4	4.3	1.3
10	-0.7	0.9	0.9	0.8	1.6	1.2
11	-2.4	1.2	-0.5	0.6	-3.4	1.5
Total means	-2.2	1.0	-2.0	0.8	-0.1	1.0

3.4 Main Experiment

3.4.1 Test Subjects

Twenty-three hearing impaired people (12 male, 11 female), aging from 34 to 87 years aged (mean = 65.2, stdv = 14.5), participated in the study as test subjects. The hearing impaired test subjects had been impaired for an average of 30.2 years (stdv = 18.3; range 8 to 72 years). Years fitted with hearing aids were 19.7 years in average, (stdv = 13.4; range 3 to 55 years). The test subjects were chosen from the Eriksholm database of test subjects. The test subjects were chosen in an attempt to meet the criterion of bilateral hearing loss of more than 40 dB at all frequencies. This criterion was chosen in order to avoid that the direct sound (the voice of the speaker) would be audible to the test subject. The pure tone average hearing loss of the test subjects was within the range of 10 to 120 dB and with an average hearing loss of 56.7 dB (stdv = 11.7 dB), calculated for the best ear aided

over the frequencies 0.5, 1.0, 2.0 and 4.0 kHz. Figure 6 shows the audiograms of all of the aided ears of the test subjects (41 ears). The thick line describes the mean value of all the aided ears. The subjects had normal to corrected vision, and were all native Danish. All test subjects participated on a voluntary basis and were paid a small amount of money for their participation, as well as travel expenses. The test subjects were contacted and asked about participation by mail (see appendix 1). All of the test subjects were informed about the aim of the test, and the test subjects approved to participate by signing a declaration of consent, which was sent to them prior to the test.

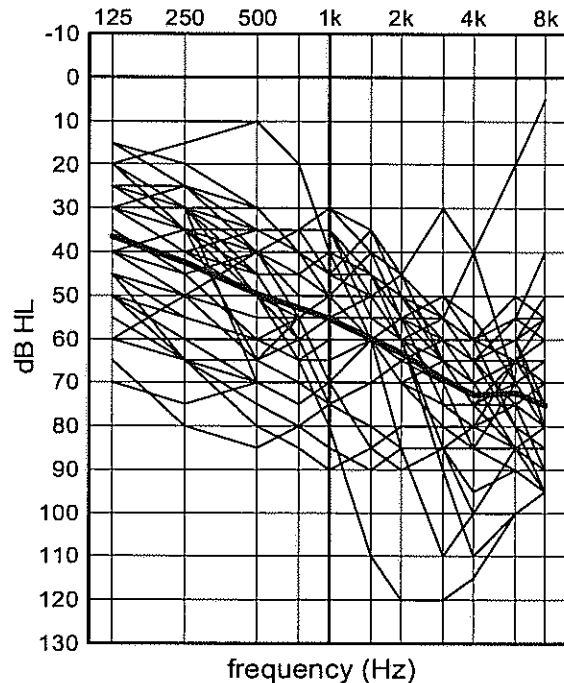


FIGURE 6: AUDIOGRAMS OF THE AIDED EARS.

Four of the test subjects had had formal training in speechreading, during early preschool years. One of the five test subjects went to a school for deaf children (without being deaf). None of the remaining nineteen test subjects had had any formal training in speechreading.

The test subjects were divided into four groups. The reason for dividing the test subjects into four groups is explained in 3.4.4. In three of the groups, the distribution was equal between men (3) and women (3). One of the groups, group 1, contained three men and two women. The average age for all four groups can be seen in table 2 below. The mean of the tone threshold, calculated as a mean of each individuals' both ears, based on the frequencies 0.5, 1.0, 2.0 and 4.0 can also be seen in the table 2.

TABLE 2: GROUP DIVISION OF THE TEST SUBJECTS

Group No.	Average Age (yr.)	No. of Men/group	No. of Women/group	Average Threshold (dBHL)
1	64	3	2	54
2	64	3	3	66
3	64	3	3	63
4	68	3	3	53

3.4.2 Live Speaker and Speech Material

See paragraph 3.3.3. The only difference regarding the speech material, between the pilot test and the main experiment, was that two different versions of the text were used in the main experiment. All four groups heard the same story but two of the groups started at a different part of it, i.e. group three and four started from the middle of the text.

3.4.3 Amplification

Insert earphones (ER 1-14A, Etymotic Research Inc.) was used in the test. They were chosen for their good damping (15-20 dB), to assure that the direct sound (the sound of the speaker) did not reach the test subject ahead of the presented sound. Further, these insert earphones compensate for the natural resonance that is lost when earplugs are inserted into the meatus. After the gain was inserted and approved by the test subject, the gain level was saved and kept during the test.

The test subjects were equipped with hearing aids in order to compensate for their hearing loss. This replaced the gain their own hearing aids normally supplied. The reason why the test subjects were not allowed to use their own hearing aids was to be able to present different delays to the test subjects. Furthermore different hearing aids have different rules of prescriptions and thereby it would be difficult to compare the results. The hearing aids used in the test were no traditional hearing aids. The amplification was realised by a DSP board inside the computer, used for transmitting the sound. The half gain rule (Lybarger, 1978) was chosen as the rule of prescription. The gain needed was individually programmed for each test subject, based on their audiograms (pure tone threshold). None of the audiograms were older than two years. Adjustments were done if the test subject was unsatisfied with the inserted gain. All of the test subjects who wore hearing aids bilaterally received bilateral stimulation. Five of the test subjects only used one hearing aid in their daily life, even if they were fitted with two hearing aids and had a bilateral hearing loss. These people only received 5 dB amplification in this study on the normally unaided ear to imitate their daily "hearing situation".

3.4.4 Procedure

The test subjects were given instructions, mainly written, but also in oral form before the test started if necessary. The distance between the test subject and the speaker was two meters. The test subject was provided with an adjustment knob, where the level of the noise was adjusted. Instructions about the adjustments on the adjustment knob were given orally.

The test procedure started with a session of training (zero ms delay) that lasted until the test subject showed consistency in answering i.e. showed a low standard deviation. The number of presses of the knob varied between the test subjects in the training session, but mainly varied between six and eight presses. The last four presses on the knob were saved and later used as a first audio-visual result with 0 ms delay. After the training session had been finished, the test continued with seven test sessions.

To evaluate the outcome of the test, five of the twenty-three test subjects were called in one week earlier than the remaining eighteen test subjects. Thus it was possible to identify possible sources of error, before continuing the test with the remaining test subjects. The test procedure for the first five test subjects (group 1) used delays in the following order: 0-training, 10, 40, 200 and 0 ms (see table 3). By re-testing the 0 ms delay, it was expected that a possible learning effect could be detected and also if a negative effect of tiredness or text difficulties existed. After the five test subjects had been through the test, a negative 'training effect' was seen for three of the test subjects, due to tiredness or the possibility that the speech material about that time in the test was so difficult and demanding on the test subject that it resulted in a worsened SNR (JFC 0) compared the SNR (JFC 0 Training) at the start. The negative 'training effect' ranged from 1.5 to 2.6 dB, with a mean of 2.2 dB. The order in which the delays were presented could also have an impact on the negative training, where a long delay (200 ms) presented before the retested 0 ms delay could result in that the level of noise was not adjusted high enough by the test subject, compared to the first tested delay (0 ms training).

To further evaluate and hopefully avoid the above mentioned negative effects in the remaining testing, the test subjects were grouped into four groups. Furthermore, the text material was reorganised so that half of the test subjects (group 1 and 2) started with the first version of the text (original text) and the other half of the test subjects (group 3 and 4) started with the second version of the text (new text). This version consisted of the same content as the first version but started from the middle of the text and ended with the first part. The presentation order of the delays was also arranged between test subjects and groups. This was done in an attempt to see if the presentation order of the delays had an impact on the worsened SNR on the 0 delay, see table 3.

TABLE 3: TEST PROCEDURE OF RESPECTIVE GROUP, ORDER OF TEXT AND ORDER OF DELAYS

<p>Group 1 Original text 10,40,200 ms delay Ascending order</p>	<p>Group 2 Original text 200,40,10 ms delay Descending order</p>
<p>Group 3 New text 10,40,200 ms delay Ascending order</p>	<p>Group 4 New text 200,40,10 ms delay Descending order</p>

Each delay was tested four times, which means that the test subject adjusted the noise level (turned up the noise level) until he or she was satisfied, and confirmed it by pressing the adjustment knob. In the sixth and seventh sessions, two new individually chosen delays were tested. These two delays were chosen on the basis of the SNRs obtained from the results of the predefined delays (0, 10, 40 and 200). This was done in order to measure the situations where the most interesting changes occurred, i.e. at the delay where a decreased SNR could be seen. If a distinct decreased performance for example could be seen between 10 and 40 ms the two individual delays were decided to be measured in between 10 and 40 ms. The last session of the test was one where only auditory presentation was available to the test subject. In the auditory only condition the noise level was obtained six times. These six adjustments vary from the four that was used when testing the different delays. The reason for this was that since the auditory only condition only was tested once, six adjustments would give a more reliable estimation of the SNR value. After the *JFC live* was finished the test subjects were asked some predefined questions concerning their subjective experience about the test and their estimated use of speechreading. The answers to some of the questions are presented in 4.4.

3.4.5 Reading Span Test

The test subject was placed in front of a computer screen. Instructions were first given in written form (see appendix 3) and thereafter in oral form. The task for the subjects, in the *Reading Span test* was; 1) to read out loud the three-word sentences presented, 2) to answer if the sentences had any meaning by saying yes or no, and 3) after a predefined number (3-6) of sentences, to repeat back the first or the last word in the sentences in correct serial order. For half of the sentences, the test subject was required to recall the final word, and in the remaining ones, the first word. The words that composed the sentences were presented one at a time for about 0.8 seconds on a computer screen. The test instructions and the sentences material were presented in Danish. Half of the sentences, i.e. 27, used in the test were without meaning, for instance 'Toget sang sangen' (*The train sang a song*), and half of the sentences had a meaning, for instance 'Kaptajnen sejlede

væk' (*The captain sailed away*). The response time after each sequence of sentences was about 2 minutes, but none of the test subjects needed more than approximately 30 seconds to answer. The result of the test was calculated in terms of the total number of correctly recalled words.

3.5 Test Approval

Both the pilot study and the main experiment were performed at Oticon Research Centre, Eriksholm, Denmark. All of the testing was performed by the author. The tests have been approved by the ethical inspection committee in Denmark named 'Den videnskabetiske komité for Bornholms, Fredriksborg, Roskilde, Storstrøms og Vest Sjællands amter'.

- ANALYSIS AND RESULTS -

The results of the main experiment will be presented in this chapter. Firstly, a general presentation of the JFC values received from the four groups will be presented. The analysis and results of the main experiment are treated in two main parts or questions, which in turn have sub-questions. The two main parts that will be presented separately in this chapter are speechreading benefit and critical delays. Finally, the subjective outcomes from the interviews are presented in brief.

4.1 Introduction

In the plots displayed below (figure 7-10), the JFC values for each test subject are plotted. The four plots represent each group separately. By showing these plots, the JFC values and the consistency of answering can be viewed. Not too surprisingly, the consistency of answering differs amongst the test subjects. Some of the test subjects answer with a high degree of consistency and are sensitive to delays where an increased delay results in higher SNR. A good example of this is test subject 1097 (group 2) in figure 8. An example of the opposite is the one received from test subject 802 (group 2), where the SNR (JFC values) decreased when the delay increased. By just looking at the plots, without looking at the statistical results, it would appear as though group 1 shows better results. However, the statistical analysis (presented below), showed no differences between the groups, even if they were tested with different versions of the text and order of delays. These differences were hence not considered further.

The plots below are based on a logarithmic time scale. This is done in order to make it clearer for the reader, since the values plotted on a linear scale would be difficult to determine and follow. The JFC values at zero delay can be seen at the x-value 1 ms, since the value zero is not applicable in a logarithmic scale. Furthermore, the A-V value (auditory signal only) can be seen at 1000 ms, even if no delay was present during this test condition. Each test subject has two zero delay values – zero delay training and the retested zero delay. The zero delay training is marked with a circle around the symbol and the retested zero delay is marked with the symbol only.

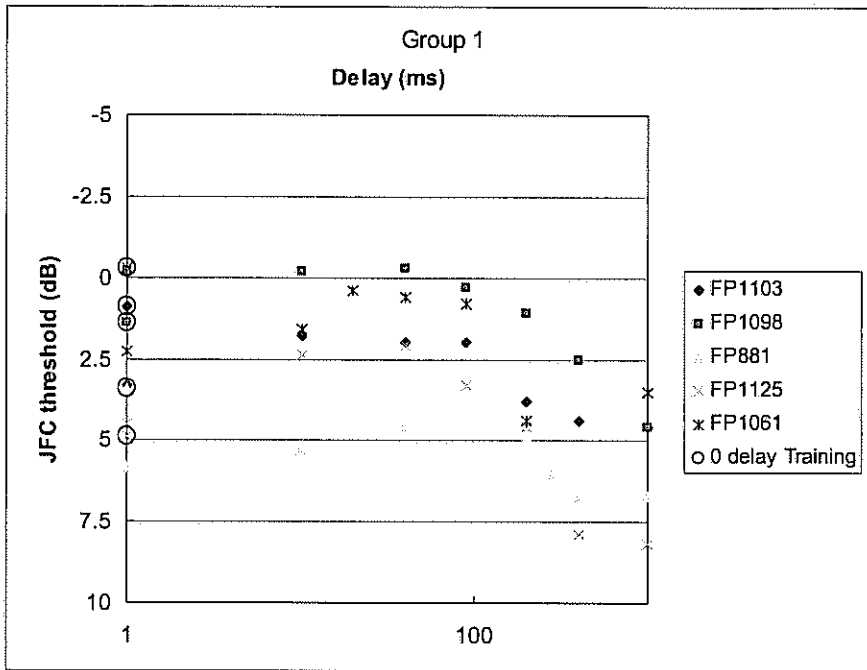


FIGURE 7: PLOT OF THE JFC VALUES OF GROUP 1.
*FP STANDS FOR TEST SUBJECT

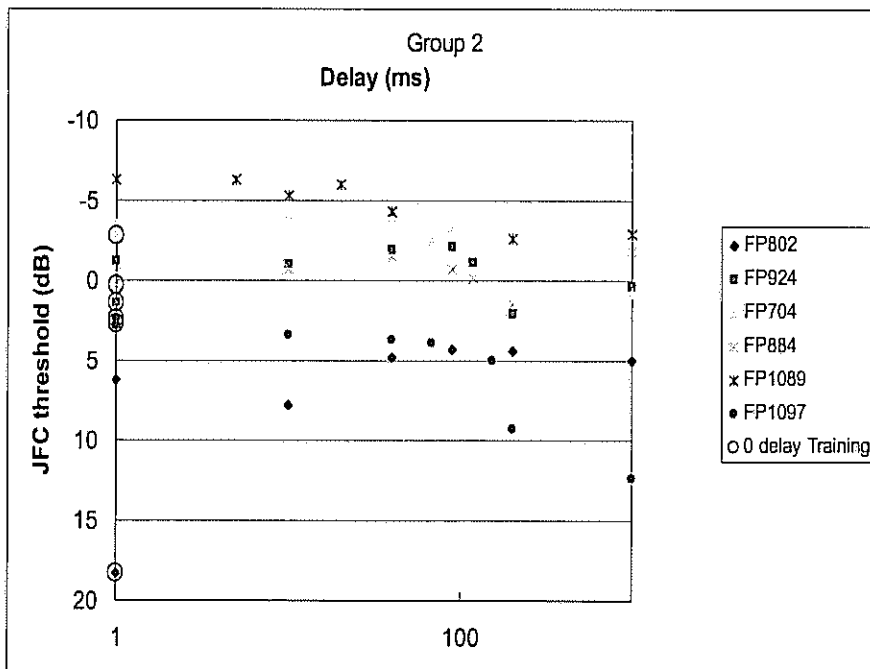


FIGURE 8: PLOT OF THE JFC VALUES OF GROUP 2.

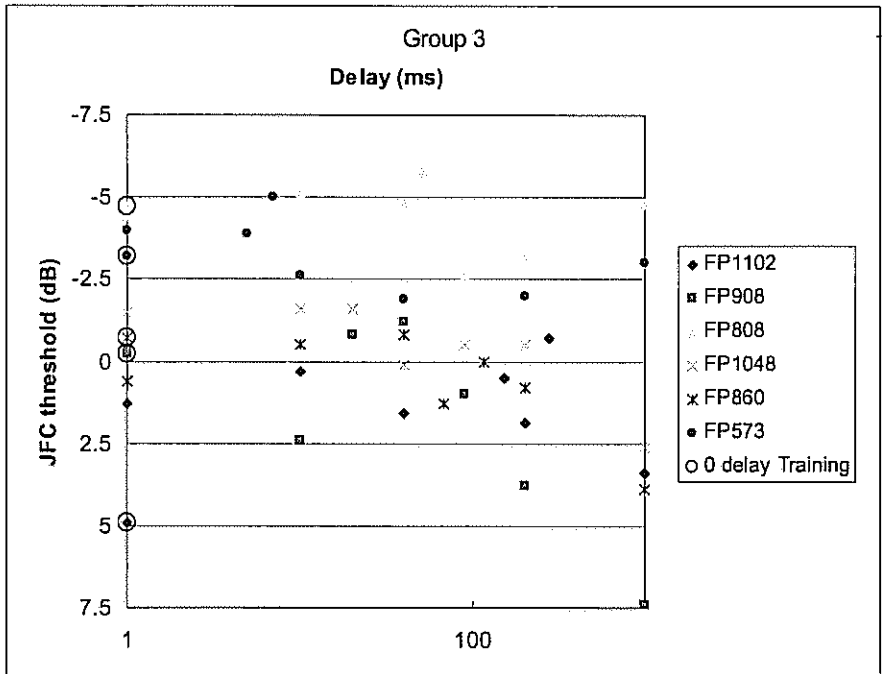


FIGURE 9: PLOT OF THE JFC VALUES OF GROUP 3.

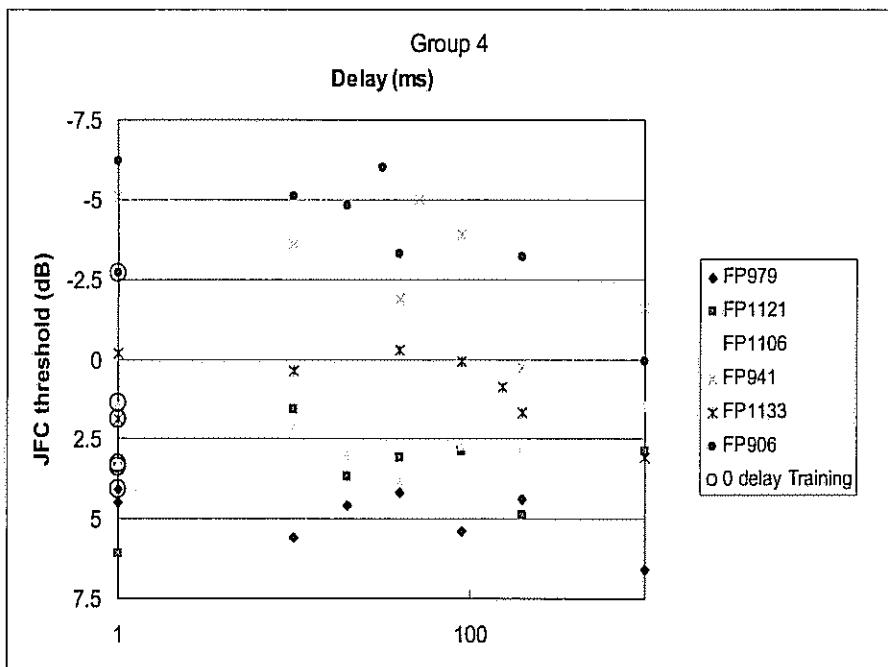


FIGURE 10: PLOT OF THE JFC VALUES OF GROUP 4.

4.2 Speechreading Benefit

4.2.1 Estimation of Speechreading Benefit

When calculating the benefit of speechreading the result presented in SNR from the auditory only presentation was subtracted from the SNR of the audio-visual presentation, 0 ms delay. This results in a measure of the benefit that the visual cues bring to the listener. This measure is widely accepted and has been applied for several years (see paragraph 2.1.3). It would also have been possible to calculate the benefit based on the difference between auditory only presentation and the 0 ms training result instead of the 0 ms. This calculation was however not applicable because of the result from two of the test subjects, 1102 and 802, where strange values from the 0 ms training (see figure 9 and 8) could be seen. These two results do not seem to be reliable since the values of the other tested delays markedly differs from the result of the 0 ms training value.

In the histogram below, see figure 11, the variation of the benefit of speechreading is plotted. This illustrates how the distribution of speechreading benefit is for the test subjects. Note the similarity between the histogram and a normal distribution with the mean 2.5 dB.

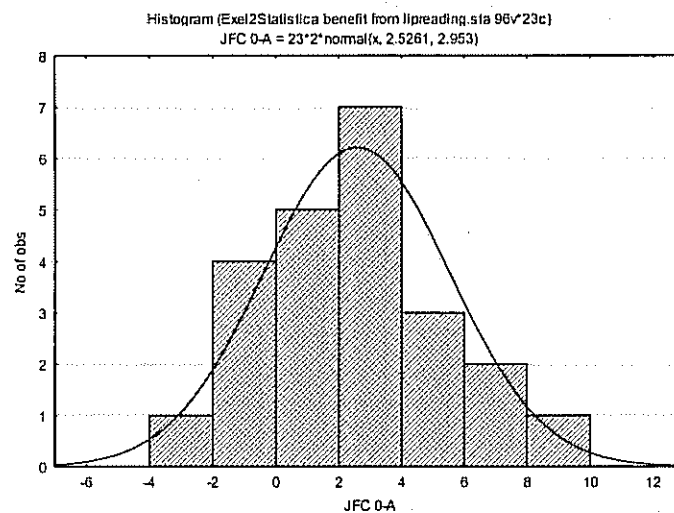


FIGURE 11: HISTOGRAM OF THE SPEECHREADING BENEFIT.

The results show that the benefit received from visual cues in the audio-visual presentation compared to the auditory presentation alone, has an average of 2.5 dB ranging from -3.2 to 9.6 dB. This result is in reasonable accordance with previous studies (Hawkins et al., (1988) 5-6 dB, Middleweerd and Plomp, (1987) 4.0 dB.), where the results also are obtained from hearing impaired listeners. A negative benefit (disadvantage) can be seen (-4 to 0 dB) for five of the test subjects. This

result is curious, since people with normal hearing benefit from additional visual cues and therefore one would assume that people with a hearing loss definitely should benefit from visual cues. Since four of the twenty-three test subjects had received some form of training in speechreading during early preschool years, it was interesting to evaluate if this training had any impact on the benefit of speechreading. The results showed that the four test subjects did not differ from the group, and their result represents the population and varied from a negative benefit of -0.25 dB to a benefit of 6.3 dB. The average of the benefit in the whole group was, as mentioned above, 2.5 dB. The long time that has passed since the training in speechreading took place has probably contributed to this result. The results found by Dodd et al. (1989), where speechreading skills could be significantly improved (about 13-14%) were based on test subjects who recently received training, and thereby the results cannot be compared. This improvement expressed in percent would correspond to an improvement of around 0.5 dB, which is the unit used for expressing the improvement in the *JFC live*. This value is based on the Articulation Index for sentences (Mueller & Killion, 1990).

4.2.2 Statistical Analyses

The results in figure 11 show a variation of the speechreading benefit. It is interesting to see whether the variation in speechreading benefit can be explained by some of the characteristics of the test subjects or the test procedure. A number of potential predictor variables have been identified. Regarding the test procedure the predictor variables are, as explained in section 3.4.4:

- Order of text
- Order of delay

Regarding the test subjects the following predictor variables have been examined:

- Congenital/non congenital hearing loss
- Age
- Monaural/binaural
- Hearing loss
- Number of years with hearing impairment
- Reading Span score, correct number of words

The hearing loss of each test subject has been calculated for the better ear over the frequencies 0.5, 1.0, 2.0 and 4.0 KHz.

Correlation Test

First a simple correlation analysis is performed between all the proposed predictors and the outcome variable. The two predictor variables sex and years with hearing aids were skipped since these two did not correlate to the speechreading benefit. Results are shown in table 5.

TABLE 4: CORRELATION TEST OF SPEECHREADING BENEFIT. SIGNIFICANT CORRELATIONS ARE INDICATED WITH BOLD ITALIC

Variable	Age	Bin/ Monaur.	PTA500Best/ Aided	No.of. yr.HI	Cong./non Congen.	ReadSpan score	Ver.of. Text	Ord.of. Delay	JFC.0-A
Age	1.00	0.04	-0.14	-0.21	-0.65	-0.61	0.08	0.07	-0.38
Bin/monaural	0.04	1.00	-0.25	0.06	0.02	0.11	0.13	0.13	-0.14
PTA500Best/Aided	-0.14	-0.25	1.00	0.12	0.13	-0.07	-0.03	-0.05	0.55
No.of.yr.HI	-0.21	0.06	0.12	1.00	0.55	0.11	0.15	-0.02	0.17
Cong./Non.cong	-0.65	0.02	0.13	0.55	1.00	0.40	0.08	-0.13	0.08
Readspan.score	-0.61	0.11	-0.07	0.11	0.40	1.00	0.25	0.08	0.22
Ver.of.Text	0.08	0.13	-0.03	0.15	0.08	0.25	1.00	-0.05	-0.02
Ord.of.Delay	0.07	0.13	-0.05	-0.02	-0.13	0.08	-0.05	1.00	-0.06
JFC.0-A	-0.38	-0.14	0.55	0.17	0.08	0.22	-0.02	-0.06	1.00

No correlation was found between congenital hearing loss and the benefit of speechreading. By this result, the findings from Ludvigsen (1981), where people with a congenital hearing loss benefited more from visual cues than people with a non congenital hearing loss, were not confirmed. This might be explained by different test procedures, measures and examined population.

The significant correlation between Reading Span score and age ($r = -0.61$), where cognitive performance (in this study working memory) decreases with an increased age, confirms the results of Hällgren et al. (2001a) and Lunner (2003). The lack of correlation between hearing loss and Reading Span score, confirms the results found by Lyxell et al. (2003). It is noteworthy that, even if a hearing loss does not negatively affect the working memory capacity, less of the cognitive skill is left for listening, since the hearing loss is more demanding on the cognitive functions, especially in unfavourable listening conditions (Lyxell et al. (2003) and Lunner (2003)). A non significant result was found between age and the benefit of speechreading. Age is negatively correlated to speechreading benefit which leads to increased age resulting in a decreased benefit of speechreading. Hearing loss is significantly and positively correlated to the benefit of speechreading ($r = 0.55$). The greater the hearing loss, the greater the benefit of speechreading. This confirms the findings of Erber (1975).

ANOVA

The analysis of variance was performed to see how the means of the defined main variables relate to the benefit of speechreading. The main variables defined were:

- Binaural/Monaural
- Congenital/Non congenital hearing loss
- Version of text
- Order of delays

The ANOVA, see table 6, showed that none of the above main variables had a significant impact ($p < 0.05$) on the benefit of speechreading (JFC 0-A).

TABLE 5: ANOVA ON SPEECHREADING THE BENEFIT

Effect	SS	Degr. of Freedom	MS	F	p
Intercept	102.8818	1	102.8818	9.943581	0.005498
Binaural/Monaural	3.7478	1	3.7478	0.362224	0.554780
Congenital/Non congenital	1.2820	1	1.2820	0.123906	0.728924
Version of text	0.0053	1	0.0053	0.000513	0.982174
Order of delays	0.1554	1	0.1554	0.015018	0.903824
Error	186.2380	18	10.3466		

Since none of the main variables had a significant impact on the benefit of speechreading, according to results of the ANOVA, the population examined will be viewed as one whole group, i.e. not as four sub-groups. The lack of significance indicates that the two different text versions used, original text and new text, did not differ in the level of complexity. The presentation order of delays, i.e. ascending or descending order, did not have an impact on the speechreading benefit either. Nor did a congenital or non congenital hearing loss have an impact on the benefit of speechreading. The impact of binaural or monaural amplification were also shown to be non-significant on the benefit of speechreading. The main variable, sex, was also tested afterwards to evaluate its impact on the speechreading benefit. No significant impact on the speechreading benefit was shown.

Multiple Linear Regression Analysis

Using a regression model, see table 7, containing two independent variables, pure tone average of best ear aided (hearing loss) and age, an analysis was performed in order to evaluate the relationship between those two variables and the speechreading benefit. The relationship between benefit of speechreading and

hearing loss was shown to be significant ($p = 0.01$). The result clearly shows that the benefit of speechreading increases with an increased hearing loss. This result is in accordance with the one received from the correlation test. The relation between the benefit of speechreading and age was not significant ($p = 0.10$). This result is also in accordance with the result received from the correlation test.

TABLE 6: MULTIPLE REGRESSION ANALYSIS OF SPEECHREADING BENEFIT VERSUS AGE VERSUS HEARING LOSS

	Beta	Std. Err. of Beta	B	Std. Err. of B	t(20)	p-level
Intercept			-0.614958	3.719180	-0.16535	0.870330
Age	-0.303374	0.176718	-0.061892	0.036053	-1.71671	0.101481
PTA500 Best/Aided	0.502579	0.176718	0.126452	0.044463	2.84396	0.010031

When the relationship between age and hearing loss and the benefit of speechreading was analysed, the results showed that age did not have a significant impact on the benefit of speechreading. A significant relation between hearing loss and the benefit from speechreading was found; and this result replicates the findings by Erber (1975), who found that an increased hearing loss results in a greater benefit from visual input. Since age does not seem to have a significant (neither negative nor positive) impact on speechreading benefit, a Simple Linear Regression Model was set up containing hearing loss as the independent variable. To make sure that nothing is disregarded, two more models were set up, one containing Reading Span score and one containing age as independent variable.

Simple Linear Regression Analysis

When the relation between hearing loss and benefit of speechreading was analysed the results showed a strong significant relation ($p = 0.007$), see figure 12 and table 8. The simple linear regression analysis was also performed on the relation between age and benefit of speechreading. The results showed that age is not significantly related to the speechreading benefit ($p = 0.078$), see figure 13 and table 9. It is, however, not far from being significant but is nevertheless not below $p = 0.05$.

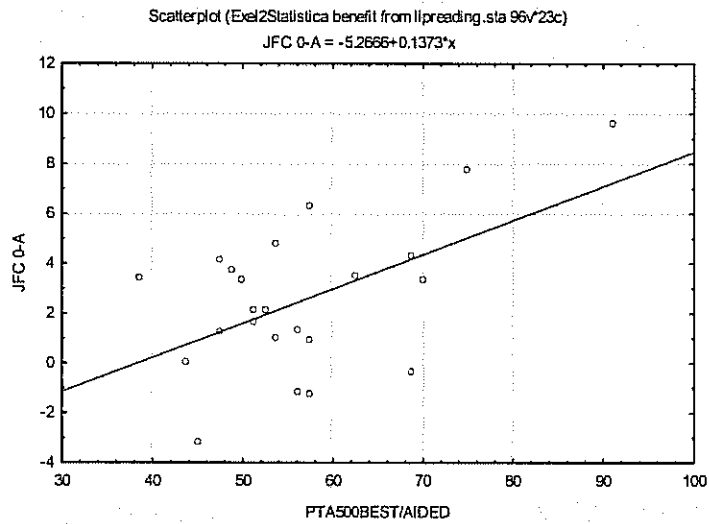


FIGURE 12: PLOT OF SIMPLE LINEAR REGRESSION ANALYSIS OF SPEECHREADING BENEFIT VERSUS HEARING LOSS INCLUDING TREND LINE.

TABLE 7: SIMPLE LINEAR REGRESSION ANALYSIS OF SPEECHREADING BENEFIT VERSUS HEARING LOSS

	Beta	Std.Err.of Beta	B	Std.Err.of B	t(21)	p-level
Intercept			-5.26659	2.663084	-1.97763	0.061243
PTA Best/Aided	0.545861	0.182840	0.13734	0.046004	2.98546	0.007052

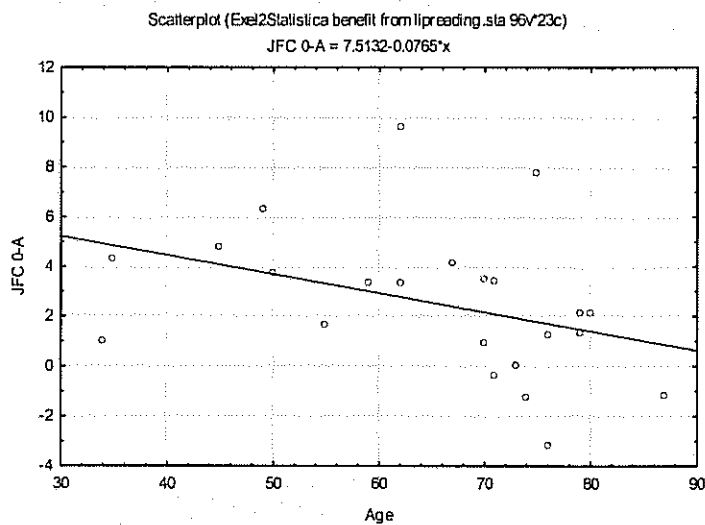


FIGURE 13: PLOT OF SIMPLE LINEAR REGRESSION ANALYSIS OF SPEECHREADING BENEFIT VERSUS AGE INCLUDING TREND LINE.

TABLE 8: SIMPLE LINEAR REGRESSION ANALYSIS OF SPEECHREADING BENEFIT VERSUS AGE

	Beta	Std.Err.of Beta	B	Std.Err.of B	t(21)	p-level
Intercept			7.513200	2.752382	2.72971	0.012554
Age	-0.375075	0.202287	-0.076520	0.041269	-1.85418	0.077813

The results show that the magnitude of the hearing loss has an impact on the benefit of speechreading. The greater the hearing loss, the greater the benefit of speechreading. Furthermore, the results show that age does not have a significant impact on the benefit of speechreading, i.e. no relation could be found that indicates that an increased age increases the benefit of speechreading or vice versa.

The number of years of hearing impairment did not have an impact on the benefit of speechreading, see appendix 5. This result does not confirm the result found by Tillberg et al. (1996), where a relationship was found between the number of years a person has had a hearing impairment and that person's ability to utilise visual cues was found. The reason for not being able to replicate the result might be explained by differences between the test used in the study by Tillberg et al. and the *JFC live*. The results from Tillberg et al. was based on 20 test subjects who were grouped according to their onset time of hearing impairment, early and late onset. This grouping was not performed in *JFC live*. Furthermore the speech material consisted of monosyllabic words presented at a 10 dB SNR (signal 75 dBSPL and noise 65 dBSPL). This presentation level and SNR differs from the *JFC live* where the SNR was based on the test subjects own subjective criteria.

The Reading Span score did not show a significant relation to the benefit of speechreading, see appendix 5 (table 13); i.e. a well functioning working memory or short term memory will not result in a greater benefit of speechreading. This result does not confirm earlier findings by Rönnberg et al. (1999), who found a significant relation between high cognitive capacity (working memory) and speechreading skill. One explanation for not having been able to reproduce the relation found by Rönnberg et al. might be that the test subjects who showed the greatest benefit of speechreading in the *JFC live* were old and an increased age decreases the performance of working memory. This is not really comparable to Rönnberg et al's study, in which a young and extremely talented speechreader (25 years old) was evaluated against a control group, consisting of test subjects whom were about the same age. Another possible explanation could be that the test subjects in *JFC live* were not stratified as in the study by Rönnberg et al.

4.3 Effect of Delay on Speechreading

4.3.1 Estimation of Critical Delay

To be able to analyse the sensitivity to delays in a statistical analysis, a critical delay, i.e. a time in milliseconds had to be estimated for each test subject. This estimation process was performed with a model which was set up in MATLAB®. The estimated critical delay was based on all of the JFC values received for each test subject (except for one). The estimation of the critical delay resulted, in most cases, in a plot with an S-shaped curve (see figure below), where the shaping was performed by MATLAB® based on the received JFC values. The \sim shaped curve (figure below), marks the critical delay and was set to be 1 dB above the lowest horizontal part of the estimated curve. In figure 14, a well matched estimation of a critical delay can be seen, a nice S-shaped curve with a critical delay marked. The estimation method is described in appendix 4.

Two of the twenty-three test subjects showed a negative benefit of speechreading. A negative benefit makes an estimation of a critical delay impossible, since it violates the model's assumptions, and therefore the results from these two test subjects were excluded. A plot which describes one of the two excluded results can be seen below, in figure 15. The plots below are in a logarithmic scale, as described above. The A-V values can be seen at 2000 ms.

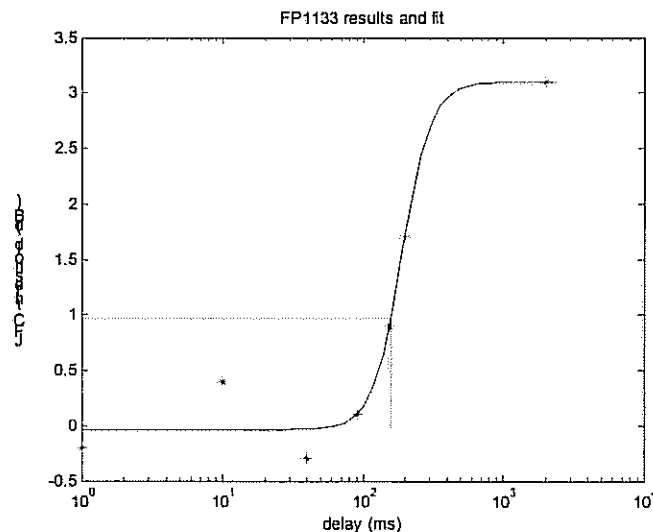


FIGURE 14: PLOT OF A SUCCESSFUL ESTIMATION OF A CRITICAL DELAY. IN THE FIGURE A * REPRESENTS A JFC VALUE, FURTHER THE ESTIMATED S-CURVE AND THE \sim THE CRITICAL DELAY CAN BE SEEN.

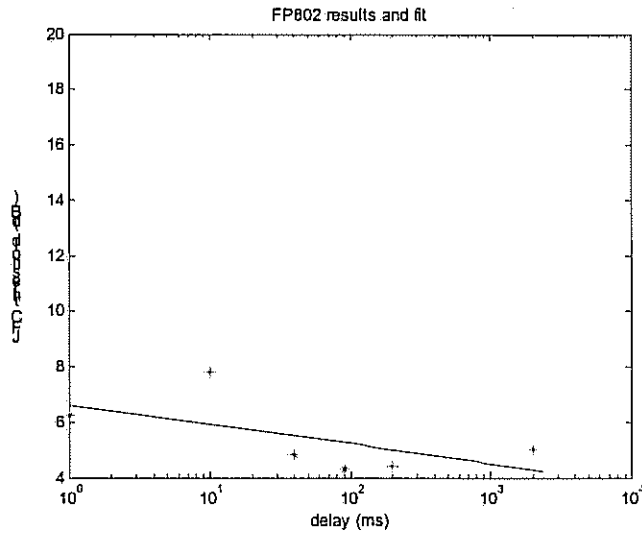


FIGURE 15: PLOT OF ONE OF THE EXCLUDED RESULTS.

Five of the test subjects did not show sensitivity to delays within the tested delays (0-200 ms). The critical delay, where the SNR increases, might occur at any delay after 200 ms up to infinity. Since no delays longer than 200 ms were tested, a critical delay was not possible to estimate on basis of these test subjects' JFC values. It would, however, be a waste to exclude all those subjects, due to lack of delays tested, since they still showed good consistency in their JFC values. A solution to the problem was that the five test subjects were given a critical delay of either 500 or 1000 ms. By giving them a critical delay a statistical analysis could be performed, and the result used. Some examples of cases where critical delays were given to the test subject are plotted below (figure 16 and 17). The choice of a critical delay of either 500 or 1000 ms was based on a subjective interpretation of the curve. If a positive change occurred at the longest delay tested, the test subject were given a critical delay of 500 ms, see figure 16. If no change occurred, the critical delay was decided to be 1000 ms, see figure 17.

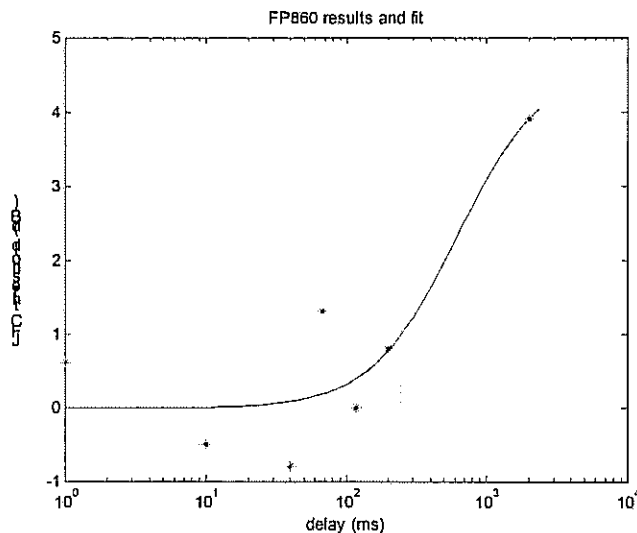


FIGURE 16: PLOT OF A GIVEN CRITICAL DELAY OF 500 MS.

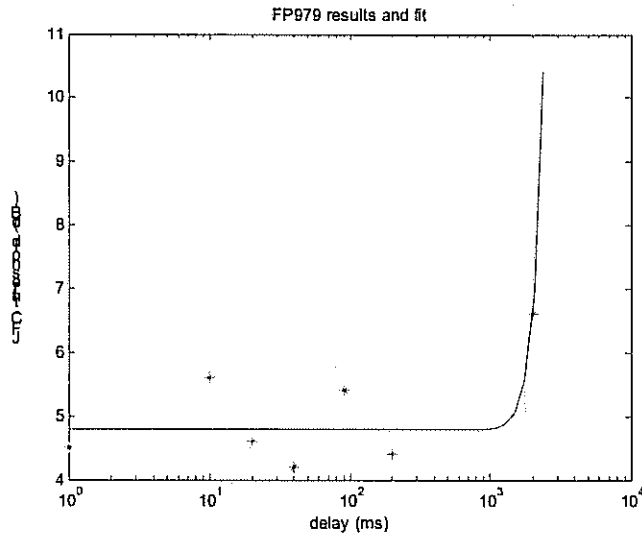


FIGURE 17: PLOT OF A GIVEN CRITICAL DELAY OF 1000 MS.

For one of the remaining twenty-one test subjects none of the two estimation modes was applicable, so an exception for this test subject (906) was made. A critical delay (70 ms) was given to the test subject. The JFC values of that test subject did not work well with the “model of speechreading benefit versus delay” which was used for the other test subjects. The estimation model failed to plot an S-shaped curve as can be seen in figure 18. To be able to keep the results received from test subject 906, a manually S-shaped curve was estimated and a critical delay of 70 ms was decided.

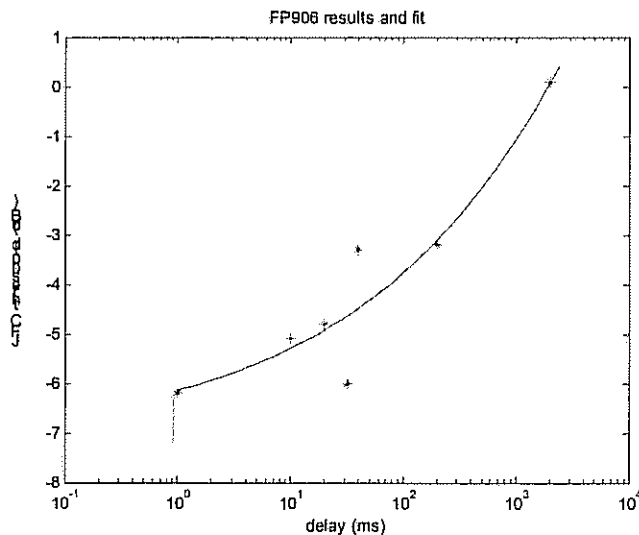


FIGURE 18: RESULT PLOTTED OF THE SUBJECT, FOR WHICH THE S-CURVE ESTIMATION FAILED AND A CRITICAL DELAY OF 70 MS WAS ASSIGNED.

The histogram below (figure 19) shows the distribution of critical delays for all test subjects. The values right below the histogram are the logarithm of the critical delay. The numbers below the logarithmic numbers are the delays transformed back into milliseconds. The reason for using a logarithmic scale is that it turned out that the time delays are best viewed on a logarithmic scale and hence the delay data are first transformed by the natural logarithm. In the statistical analysis the logarithmic value was used but then transformed back again to a linear scale for interpretation. The two test subjects with values of critical delays of 2.0 -2.5 (7-12 ms) – the first pile in the histogram - are the test subjects whom are the most sensitive to delays. The long delays (500 or 1000 ms), which five of the test subjects got assigned, can be seen in the histogram at 6.0 to 7.0 (403-1097).

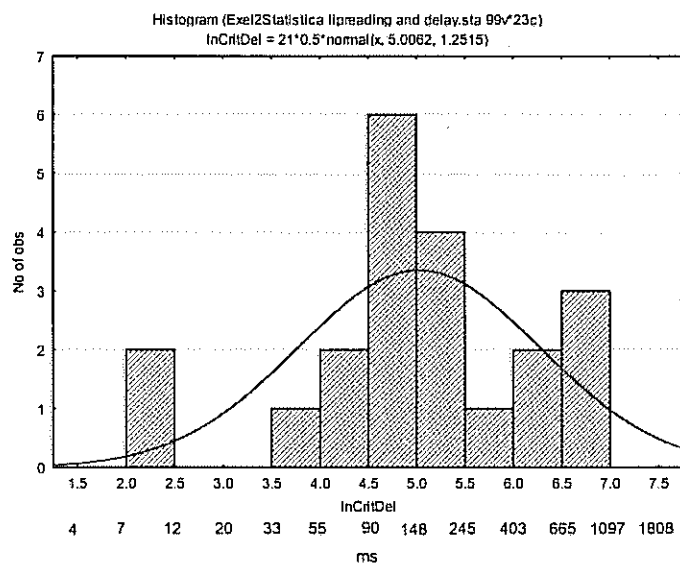


FIGURE 19: HISTOGRAM OF THE CRITICAL DELAYS.

4.3.2 Statistical Analyses

The results in figure 19 show a considerable variation of the critical delays. In order to evaluate why this is the case, some characteristics of the test subjects has been defined. They are basically the same as the ones used in the analysis of speechreading benefit, but one more characteristic has been added – number of years with hearing aid. As noted above, the natural logarithm of the critical delay is used throughout the analysis.

Correlation Test

First a simple correlation analysis is performed between all the proposed predictors and the outcome variable. Results are shown in table 10.

TABLE 9: CORRELATION TEST OF CRITICAL DELAY

Variable	Sex	Age	Bin/ Monaural	PTA500Best/ Aided	No.yr.HI	No.yr. with.HA	Cong./ Non cong	LnCrit Del	Read.Span. Corr.words	Ver.of Text	Ord.of Delays
Sex	1,00	-0,18	-0,31	-0,05	-0,16	0,06	0,09	-0,16	0,55	0,05	0,15
Age	-0,18	1,00	-0,02	-0,11	-0,31	-0,39	-0,64	0,22	-0,63	0,13	-0,04
Bin/Monaural	-0,31	-0,02	1,00	-0,24	0,16	0,30	0,05	0,26	0,13	0,14	0,09
PTA500Best/Aided	-0,05	-0,11	-0,24	1,00	0,00	0,07	0,10	0,14	-0,03	0,02	-0,01
No.yr.HI	-0,16	-0,31	0,16	0,00	1,00	0,48	0,33	-0,14	0,18	0,01	-0,09
No.yr.HA	0,06	-0,39	0,30	0,07	0,48	1,00	0,84	-0,23	0,27	0,15	-0,01
Cong./Non cong.	0,09	-0,64	0,05	0,10	0,33	0,84	1,00	-0,26	0,42	0,09	-0,09
LnCritical Delay	-0,16	0,22	0,26	0,14	-0,14	-0,23	-0,26	1,00	-0,06	-0,03	-0,17
ReadSpan.corr.words	0,55	-0,63	0,13	-0,03	0,18	0,27	0,42	-0,06	1,00	0,17	0,11
Ver.of Text	0,05	0,13	0,14	0,02	0,01	0,15	0,09	-0,03	0,17	1,00	-0,05
Ord.of Delay	0,15	-0,04	0,09	-0,01	-0,09	-0,01	-0,09	-0,17	0,11	-0,05	1,00

The results received from the correlation test showed that neither of the predictors was significantly correlated to the critical delay. Age is significantly correlated to congenital/non congenital hearing loss ($r = -0.64$). Sex is significantly correlated to Reading Span score (number of correct words) ($r = 0.55$). This correlation, where women perform better than men, can be explained by the fact that the women were younger than the men. Number of years fitted with hearing aid is not surprisingly significantly correlated to congenital/non congenital hearing loss ($r = 0.84$) and to the number of years of hearing impairment ($r = 0.48$).

ANOVA

Despite the results of the correlation analysis an analysis of variance was performed to see how the means of the defined main variables relate to the critical delay. The defined main variables were:

- Binaural/Monaural
- Congenital/Non congenital hearing loss
- Version of Text
- Order of Delays

The results from the ANOVA test showed that none of the main variables had a significant impact ($p < 0.05$) on the critical delay, see table 11.

TABLE 10: ANOVA CRITICAL DELAY

Effect	SS	Degr. of Freedom	MS	F	p
Intercept	238.3875	1	238.3875	151.8271	0.000000
Bin/Monaural	2.8534	1	2.8534	1.8173	0.196408
Cong/Noncong	2.6289	1	2.6289	1.6744	0.214044
Ver.text	0.1095	1	0.1095	0.0697	0.795100
Ord.delays	1.5494	1	1.5494	0.9868	0.335317
Error	25.1220	16	1.5701		

None of the main variables are close to being significant. The main variable, sex, was also tested afterwards to evaluate its possible impact on the critical delay. No significant impact could be seen ($p = 0.95$). Despite all non significant results, one positive observation can be made: the four groups can be seen as one, since the version of text and order of delays did not have an impact on the critical delay.

Simple Linear Regression Analysis

A Simple Linear Regression Analysis was performed to see how hearing loss was related to the critical delay. The result was not significant ($p = 0.55$). An interesting observation can, however, be made from the plot in figure 20.

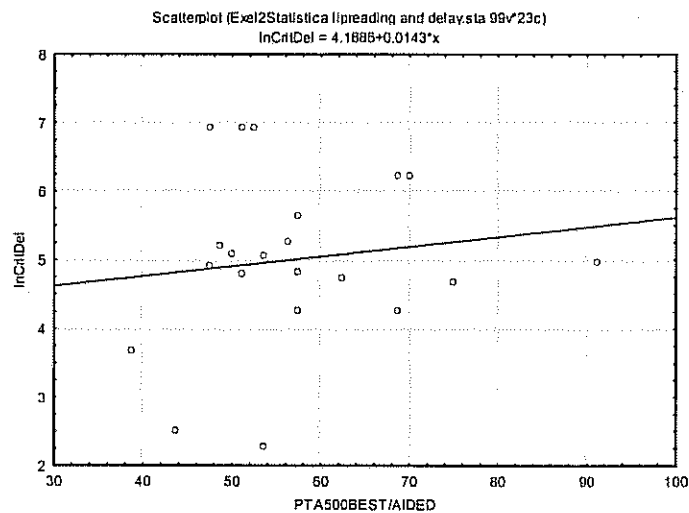


FIGURE 20: PLOT OF CRITICAL DELAY VERSUS HEARING LOSS INCLUDING TREND LINE.

Even if the relation is weak – or non-existing – it is striking that the three test subjects that have the smallest critical delays have hearing losses in the lower end of the range. The relation found between greater hearing loss and benefit of speechreading, described above, would in relation to this result, mean that people with great hearing losses are so dependent on the visual input that a delay does not annoy them, they can still benefit from visual cues, even if the delays are long. Minor hearing losses result in more use of the audio input, and therefore a higher sensitivity to delays. With this result in mind, it seems reasonable to assume that people with normal hearing are even more sensitive to delays, compared to people with small hearing losses.

This hypothesis can actually be tested with data from the pilot test, where eleven normal hearing test subjects participated. They were only tested with one delay, 40 ms. The JFC value obtained at 40 ms delay, received from each test subject, was subtracted from the result at 0 ms delay. The difference, expressed as the JFC 40-0, has been plotted in a histogram, shown below (figure 21). The histogram bars between 1 to 2 dB correspond to a critical delay at about or less than 40 ms. The results of the test subjects who performed better with a delay are plotted between -1.0 and 0.0 dB. The two test subjects that showed a performance between 0.5 and 1 dB might have a critical delay that is greater than 40 ms. Thus, these pilot data do actually not suggest that normal hearing people are much more sensitive to delays than people with a moderate hearing loss.

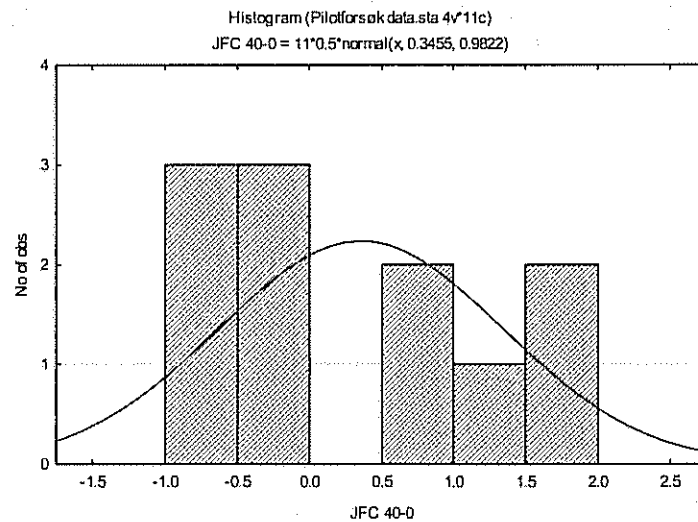


FIGURE 21: HISTOGRAM OF LOSSES IN JFC PERFORMANCE FOR NORMAL HEARING PEOPLE. PRESENTED IN DB AT A DELAY OF 40 MS.

The conclusion from this result is that people with a great hearing loss might be more dependent of good glasses than of hearing aids with small delays. As long as the hearing aid gives amplification enough, the hearing aid in combination with glasses constitutes a perfect help in speechreading.

4.4 Subjective Outcomes

After the *JFC live* was finished the test subjects were asked questions about the test. All test subjects were asked the same questions. The answers of the questions were compared, and some of them are presented below:

- All but one of the test subjects found it easier to understand what was being said and easier to listen when they could see the speaker, during audio-visual presentation compared to the auditory only presentation.
- 65 % of the test subjects reported that they looked at the mouth of the speaker when trying to utilise speechreading in the test, the remaining test subjects said they looked at the whole face.
- 91 % of the test subject stated that they utilised speechreading every day.
- 52 % of the test subjects could notice that the sound and movements of the mouth of the speaker was sometimes desynchronized.
- 69 % of the test subjects reported that they were not annoyed by the delays presented during the test.

The result where all but one of the test subjects found it easier to listen during audio-visual presentation compared to auditory only presentation is a little surprising. The expected answer would be that all of the test subjects found it easier when the visual input was available. It could be expected that it was one of the test subjects who received a negative benefit of speechreading who reported this, but it was not. The test subject who reported it, had a benefit of visual cues but was probably not aware of it. From the answers, it seems like hearing impaired people are dependent on speechreading and use it daily (91 % of the test subjects), which was an expected result. The high number of test subjects who stated that they were not annoyed by the delays (69 %), might be explained by the fact that people with great hearing losses are dependent on the visual input and therefore can have indulgence with the presence of delays. One test subject tried to give an explanation on the impact of delays on the speech perception: "I was helped by being able to see the speaker despite the fact that sound and picture did not match; it is like the brain manages to cope with the delay, it thinks'; all right, there is a delay', but the information is still there". This argument seems reasonable and might be applied to most hearing impaired people.

- FINAL DISCUSSION -

Before the beginning of this study it was presumed that all of the test subjects would benefit from the visual cues in the audio-visual presentation. This belief was based on studies where normal hearing test subjects benefited from visual cues (Sumbly & Pollack, 1954). The benefit of speechreading was evaluated and the results showed that hearing impaired people benefit from speechreading. This finding supports hypothesis 1. The average benefit was 2.5 dB, which is similar to the benefit found in the pilot test (2.05 dB) based on normal hearing test subjects. These results confirm the result from several studies (Rönnberg et al., (1983), Hygge et al., (1992), Lyxell and Rönnberg, (1989) and Lyxell and Rönnberg, (1991)), where it was found that hearing impaired people are no better in utilising visual cues compared to normal hearing people. The small difference in benefit of speechreading confirms the result by Middelweerd and Plomp (1987) where the speechreading benefit of young normal hearing and elderly hearing impaired people was evaluated, and the difference was found to be 0.6 dB. Middelweerd and Plomp (1987) found also that the young test subjects showed greater variation in benefit of speechreading. In this study the standard deviations was 3.9 dB for the pilot test and 2.9 dB for the main experiment. From a simple F-test it was shown that the standard deviations were not significantly different.

Furthermore a correlation was found in this study between speechreading benefit and hearing loss, where a greater hearing loss is accompanied by a greater benefit of speechreading. This result supports hypothesis 2. The correlation found in this study does not confirm the result by Walden et al. (1993). The benefit of speechreading in the study by Walden et al. did not differ between middle-aged and elderly test subjects with moderate to severe hearing losses. The study of Walden et al. could maybe have found the same result as this study if the test subjects were grouped also after degree of hearing loss, and not only after middle-aged and elderly with moderate to severe hearing losses. The result from this study does however confirm the result found by Walden et al. concerning the correlation between age and speechreading benefit. An increased age did not tend to be correlated to the speechreading benefit in this study. The correlation was however not far from being significant (see paragraph 4.2.2).

It was assumed that a well developed working memory would result in a greater benefit of speechreading (hypothesis 3). This assumption was based on the result by Rönnerberg et al. (1999), where a significant relation between high cognitive function (working memory) and speechreading skill was found. The significant correlation was however based on an extremely talented speechreader versus two different reference groups consisting of normal hearing and hearing impaired people. In this study a significant correlation could however not be found, i.e. no support was found for hypothesis 3. The test subjects in the study by Rönnerberg et al. were all young, 22-30 years. The group in this study was not stratified in terms of age, skill in speechreading or other possible factors, with one exception that all the test subjects were hearing impaired. The lack of stratification might explain why the result by Rönnerberg et al. could not be confirmed.

Most earlier studies have studied the impact of long delays on speech perception, in normal hearing test subjects. At the outset of this study it was assumed that hearing impaired people, especially those with large hearing losses, were critically dependent of the visual input because of their reduced hearing, and they would therefore be disturbed by short delays. The assumption was not in accordance with the results. The results showed that the majority of the test subjects were disturbed within the tested delays (0-200 ms), i.e. support for hypothesis 4 was found, but in general not by short delays (< 40 ms). This result is in accordance with McGrath and Summerfield (1985), who found that delays shorter than 40 ms might be acceptable without having any significant effect on auditory and visual perception of speech.

A few test subjects were, however, sensitive to shorter delays (< 40 ms). These test subjects had hearing losses in the low end of the spectrum. The conclusion from this is that, on average, hearing impaired people are not sensitive to short delays, with a few exceptions. For those, long delays in hearing aids might be a problem. The small delays that are introduced in the hearing aids on the market (4-12 ms) today would probably not have a negative impact on the benefit of speechreading. Since the test subjects were able to tolerate large delays before they showed any disturbance, it can be concluded that hearing impaired listeners, especially those with large hearing losses, are so dependent on the visual input that large delays do not bring annoyance. It is important that the disturbance of delays discussed here is only seen in the perspective of speech perception and not in the perspective of speech production, where shorter delays might affect and result in disturbed speech (Stone & Moore, 2002).

- REFERENCES -

- Agnew, J., & Thornton, J.M. (2000). Just noticeable and objectionable group delays in digital hearing aids. *Journal of the American Academy of Audiology*, 11, 330-336.
- Arlinger, S., & Gustafsson, H.Å. (1994). Masking of speech by amplitude-modulated noise. *Journal of the Acoustical Society of America*, 95, 518-529.
- Baddeley, A.D. (1986). *Working memory*. Oxford: Oxford University Press.
- Brand, T. (1969). *Analysis and optimization of psychophysical procedures in audiology*. Ph.D. Thesis. Dem Fachbereich Physik der Universität Oldenburg.
- Byers, V.W., & Liberman, L. (1959). Lipreading performance and the rate of the speaker. *Journal of Speech and Hearing Research*, 2, 271-276.
- Campbell, R. & Dodd, B. (1980). Hearing by eye. *The Quarterly Journal of Experimental Psychology*, 32, 85-99.
- Committee on Hearing, Bioacoustics, and Biomechanics. (1988). Speech understanding and aging. *Journal of the Acoustical Society of America*, 83, 859-895.
- Cowan, N. (1998). Visual and auditory working memory capacity. I: *Trends in Cognitive Sciences*, nr 3, 77-78.
- Daneman, M., & Carpenter, P.A. (1980). Individual differences in working memory and reading. *Journal of Verbal Learning and Verbal Behaviour*, 19, 450-466.
- Daneman, M., & Greene, I. (1986). Individual differences in comprehending and producing words in context. *Journal of Memory and Language*, 25, 1-18.
- Dixon, P., LeFevre, J-A., & Twilley, L.C. (1988). Word knowledge and working memory as predictors of reading skill. *Journal of Educational Psychology*, 4, 465-472.
- Dodd, B., Plant, G., & Gregory, M. (1989). Teaching lip-reading: the efficacy of lessons on video. *British Journal of Audiology*, 23, 229-238.
- Erber, NP. (1975). Auditory-visual perception of speech. *Journal of Speech and Hearing Disorders*, 40, 481-492.

- Grant, K.W., & Seitz, P.F. (1998). Measures of auditory-visual integration in nonsense syllables and sentences. *Journal of the Acoustical Society of America*, 104, 2438-2450.
- Grant, K.W., & Seitz, P-F. (2000). The use of visible speech cues for improving auditory detection of spoken sentences. *Journal of the Acoustical Society of America*, 108, 1197-1208.
- Hagerman, B. (1984). Clinical measurement of speech reception threshold in noise. *Scandinavian Audiology*, 13, 57-63.
- Hawkins, J.E. Jr., & Stevens, S.S. (1950). The masking of pure tones and of speech by white noise. *Journal of the Acoustical Society of America*, 22, 6-13.
- Hawkins, DB., Montgomery, AA., Mueller HG. and Sedge, RK. (1988). Assessment of speech intelligibility by hearing impaired listeners. In: Berglund, B., Berglund, U., Karlson, J. and Lindvall, T. (Eds.) Noise as a public health problem: Vol. 2. Hearing, communication, sleep and nonauditory physiological effects. 241-246. Stockholm: Swedish Council for Building Research.
- Houston, K.T., & Montgomery, A.A. (1997). Auditory-visual integration: A practical approach. *Seminars in Hearing*, 18, 141-151.
- Hygge, S., Rönnerberg, J., Larsby, B., & Arlinger, S. (1992). Normal-hearing and hearing-impaired subjects' ability to just follow conversation in competing speech, reversed speech, and noise backgrounds. *Journal of Speech and Hearing Research*, 35, 208-215.
- Hällgren, M., Larsby, B., Lyxell, B., & Arlinger, S. (2001a). Evaluation of a cognitive test battery in young and elderly normal-hearing and hearing impaired persons. *Journal of the American Academy of Audiology*, 12, 357-370.
- Hällgren, M., Larsby, B., Lyxell, B., & Arlinger, S. (2001b). Cognitive effects in dichotic speech testing in elderly persons. *Ear and Hearing*, 22, 120-129.
- Kaplan, H. (1997). Speechreading. *Seminars in Hearing*, 18, 129-140.
- König, E. (1965). "Data discussed at round table meeting". *International Journal of Audiology*, 4, 72-75.
- Lansing, C.R., & McConkie, G.W. (1994). A new method for speechreading research: tracking observers' eye movement. *Journal of the Academy of Rehabilitative Audiology*, 27, 25-43.
- Larsby, B., & Arlinger, S. (1994). Speech recognition and Just-Follow-Conversation tasks for normal-hearing and hearing-impaired listeners with different maskers. *Audiology*, 33, 165-176.
- Lidestam, B., Lyxell, B., & Andersson, G. (1999). Speech-reading: cognitive predictors and displayed emotion. *Scandinavian Audiology*, 28, 211-217.

- Lidestam, B., Lyxell, B., & Lundeberg, M. (2001). Speech-reading of synthetic and natural faces. Effects of contextual cueing and mode of presentation. *Scandinavian Audiology*, 30, 89-94.
- Lonka, E. (1995). Speechreading instruction for hard-of-hearing adults. Effects of training face-to-face and with a video programme. *Scandinavian Audiology*, 24, 193-198.
- Ludvigsen, C. (1981). *Operation Helen*. Copenhagen: Stougaard Jensen.
- Lunner, T. (2003). Cognitive functions in relation to hearing aid use. *International Journal of Audiology*, 42, 49-58.
- Lybarger, S.F. (1978). Selective amplification – a review and evaluation. *Journal of the Acoustical Society of America*, 3, 258-266.
- Lyxell, B., & Rönnerberg, J. (1987). Guessing and speechreading. *British Journal of Audiology*, 21, 13-20.
- Lyxell, B., & Rönnerberg, J. (1989). Information processing skill and speech-reading. *British Journal of Audiology*, 23, 339-347.
- Lyxell, B., & Rönnerberg, J. (1991). Word discrimination and chronological age related to sentence-based speech-reading skill. *British Journal of Audiology*, 25, 3-10.
- Lyxell, B., Rönnerberg, J., Andersson, J., & Linderöth, E. (1993). Vibrotactile support: initial effects on visual speech perception. *Scandinavian Audiology*, 24, 179-183.
- Lyxell, B., Johansson, K., & Rönnerberg, J. (1996). Facial expressions and speechreading performance. *Scandinavian Audiology*, 25, 97-102.
- Lyxell, B., Andersson, U., Borg, E., & Ohlsson, I-S. (2003). Working memory and phonological processing in deafened adults and individuals with a severe hearing impairment. *International Journal of Audiology*, 42, 86-89.
- MacLeod, A., & Summerfield, Q. (1987). Quantifying the contribution of vision to speech perception in noise. *British Journal of Audiology*, 21, 131-141.
- MacLeod, A., & Summerfield, Q. (1990). A procedure for measuring auditory and audio-visual speech-reception thresholds for sentences in noise: rationale, evaluation, and recommendations for use. *British Journal of Audiology*, 24, 29-43.
- Massaro, D.W., Cohen, M.M., & Smeele, P.M.T. (1996). Perception of asynchronous and conflicting visual and auditory speech. *Journal of the Acoustical Society of America*, 100, 1777-1786.
- McCormick, B. (1980). The assessment of audio-visual and visual speech discrimination skills in aural rehabilitative programmes. Taylor, I.G. & Markides, A. (Eds.) *Disorders of Auditory function III* (p. 307-321). London: Academic Press.

- McGrath, M., & Summerfield, Q. (1985). Intermodal timing relations and audio-visual speech recognition by normal hearing adults. *Journal of the Acoustical Society of America*, 77, 678-685.
- McGurk, H., & MacDonald, J. (1976). Hearing lips and seeing voices. *Nature*, 264, 746-748.
- Middelweerd, M., & Plomp, R. (1987). The effect of speechreading on the speech-reception threshold of sentences in noise. *Journal of the Acoustical Society of America*, 82, 2145-2147.
- Mueller, G.H., & Killion, M.C. (1990). An easy method for calculating the articulation index. *The Hearing Journal*, 9, 14-17.
- Neumann, J., & Søgaard Jensen, N. (2000). *Just Follow Conversation – Eriksholm Version* (Report: 052-08-01). Snekkersten: Oticon A/S Research Centre Eriksholm, Snekkersten, Denmark.
- Oyer, H.J. (1961). Visual and auditory training for adults. In: Katz, J. Ed. *The Handbook of Clinical Audiology*. Baltimore: Williams and Williams 3rd.
- Pandey, P.C., Kunov, H., & Abel, S.M. (1986). Disruptive effects of auditory signal delay on speech perception with lipreading. *The Journal of Auditory Research*, 26, 27-41.
- Pichora-Fuller, M.K., Schneider, B.A., and Daneman, M. (1995). How young and adults listen to and remember speech in noise. *Journal of the Acoustic Society of America*, 97, 593-608.
- Plomp, R. (1978). Auditory handicap of hearing impairment and the limited benefit of hearing aids. *Journal of the Acoustic Society of America*, 63, 533-549.
- Reisberg, D., McLean, J., & Goldfield, A. Easy to hear but hard to understand: A lip-reading advantage with intact auditory stimuli. In: Dodd, B., & Campbell, R., eds. *Hearing by eye: The psychology of lipreading*. London: LEA, 1987; 97-113.
- Rosen, S., & Corcoran, T. (1982). A video-recorded test of lipreading for British English. *British Journal of Audiology*, 16, 245-254.
- Ross, M. (1998). Ways to improve listening and hearing. In: Carmen, R. *The consumer handbook on hearing loss and hearing aids*. Sedona: Auricle Ink Publishers.
- Rönnberg, J., Öhngren, G., & Nilsson, L.-G. (1983). Speechreading performance evaluated by means of TV and real-life presentation. *Scandinavian Audiology*, 12, 71-77.
- Rönnberg, J., Samuelsson, S., & Arlinger, S. (1996). Lipreading with auditory low-frequency information. *Scandinavian Audiology*, 25, 127-132.
- Rönnberg, J., Andersson, J., Samuelsson, S., Söderfeldt, B., Lyxell, B., Risberg, J. (1999). A speechreading expert: The case of MM. *Journal of Speech and Hearing Research*, 42, 5-20.
- Rönnberg, J. (2003). Working memory for speechreading and poorly specified linguistic input: applications to sensory aids. *The Hearing Review*, 10, 26-31.

- Sims, D.G. (1978). Visual and auditory training for adults. In Katz, J. Ed. *The Handbook of Clinical Audiology*. Baltimore: Williams and Wilkins 3rd ed.
- Stone, M.A., & Moore, B.C.J. (1999). Tolerable hearing aid delays. I. Estimation of limits imposed by the auditory path alone using simulated hearing losses. *Ear & Hearing, 20*, 182-192.
- Stone, M.A., & Moore, B.C.J. (2002). Tolerable hearing aid delays. II. Estimation of limits imposed during speech production. *Ear & Hearing, 23*, 325-338.
- Sumby, W. W., & Pollack, I. (1954). Visual contribution to speech intelligibility in noise. *Journal of the Acoustical Society of America, 26*, 212-215.
- Summerfield, Q. (1987). Some preliminaries to a comprehensive account of audio-visual speech perception. In: Dodd, B., & Campbell, R. (Eds.) *Hearing by eye: The psychology of lipreading*. London: LEA, 1987; 3-51.
- Tillberg, I., Rönnberg, J., Svärd, I., & Ahlner, B. (1996). Audio-visual speechreading in a group of hearing aid users. The effects of onset age, handicap age, and degree of hearing loss. *Scandinavian Audiology, 25*, 267-272.
- Tye-Murray, N. (1992). Preparing for communication interactions: The value of anticipatory strategies for adults with hearing impairment. *Journal of Speech and Hearing Research, 35*, 430-435.
- Walden, B.E., Busacco, D.E., & Montgomery, A.A. (1993). Benefit from visual cues in auditory-visual speech recognition by middle-aged and elderly persons. *Journal of Speech and Hearing Research, 36*, 431-436.
- Walden, K. & Cord, M. T. (2001). Effects of amplification and speechreading on consonant recognition by persons with impaired hearing. *Ear and Hearing, 22*, 333-341.

APPENDIX

Appendix 1: Invitation Letter

Snekkersten, 6. august 2004

Kære ,

Du anmodes hermed om at deltage i forskningsprojektet; ”*Taleforståelighedstest med auditivt og visuelt input*” som i øjeblikket afvikles på Oticons forskningscenter, *Eriksholm*. Derfor fremsendes deltagerinformation om forsøget, med håb om, at det måske kan have interesse for dig. Projektet er et eksamensprojekt og laves som et samarbejde mellem Eriksholm og Lunds universitet.

Forsøget udføres af en svensk forsøgsleder, Louise Prytz. Hvis du har svært at ved at forstå svensk, beder vi dig give besked om det.

• Såfremt du er interesseret i at deltage, er følgende tidspunkt reserveret til besøget,

Xdag den X/X kl. X.00

Besøget forventes at vare ca. **2 timer**. Som noget nyt vedlægger vi informationsmateriale omkring forsøget. Efter gennemlæsning af deltagerinformationen bedes du kontakte Jette Damm Lützhøft, med oplysning om, hvorvidt du er interesseret i at deltage, samt om tidspunktet passer dig. Før besøget er det vigtig, at du har fået dine ører eftersat for ørevoks af en ørelæge. Forskningscenterets adresse står her under og bus 353 holder lige ved døren.

Kongevejen 243
3070 Snekkersten

Vi håber, at du vil deltage som forsøgsperson i projektet. Hvis du har nogle spørgsmål er du velkommen til at kontakte Louise eller Søren, på tlf.: **49 22 35 22** eller på e-mail: **lpr@oticon.dk** eller **slu@oticon.dk**.

Med venlig hilsen, Louise Prytz og Søren Laugesen

Appendix 2: Instructions to JFC Live

Instruktion

Du skal lytte til en kvinde, der læser op fra en tekst. Teksten du skal lytte til består af korte uddrag, der er klippet sammen i tilfældig rækkefølge. Talen vil komme fra høretelefonerne. I denne test er det vigtigt at du hele tiden kigger på talarens ansigt når du lytter til teksten.

Du vil hele tiden blive forstyrret af et støjsignal. Du kan selv regulere styrken af støjen ved at dreje på en knap. Styrken af talen vil være konstant.

I begyndelsen vil støjen være meget svagere end talen. Din opgave er at indstille styrken af støjen, så du lige netop kan forstå, hvad der bliver sagt, når du virkelig koncentrerer dig. Det betyder, at der er enkelte ord, som du ikke opfatter, men du skal forstå meningen af det, der bliver sagt.

Når du har reguleret støjen til en styrke, hvor du mener, at du lige netop forstår, hvad der bliver sagt, trykker du på knappen. Herefter falder styrken af støjen, så den igen bliver meget svagere end talen. Du skal nu igen regulere styrken af støjen, så du lige netop kan forstå, hvad der bliver sagt. Denne procedure vil blive gentaget flere gange.

Når du indstiller styrken af støjen, er det en god idé at prøve at eksperimentere lidt – dvs. prøve at indstille styrken både lidt for lavt og lidt for højt.

Hvis der er noget, du er i tvivl om, er du velkommen til at spørge!

Appendix 3: Reading Span Instructions

Instruktion

”Dette er en svær opgave, men gør det så godt du kan.

Du vil se et antal korte sætninger på skærmen. Hver sætning indeholder tre ord. Sætningerne vil blive vist ét ord ad gangen. En del av sætningerne vil være mærkelige eller absurde – de giver ingen mening for eksempel: *Toget spiste græs*, mens andre vil være helt normale og give mening for eksempel: *Hesten spiste æblet*. Efter hver sætning vil der være en kort pause.

Læs sætningen højt for dig selv. Når du har læst sætningen, skal du sige ”JA” højt og tydeligt, hvis sætningen gav mening, og du skal sige ”NEJ”, hvis sætningen ikke gav mening.

Når der har været et antal sætninger, vil der stå ”Gentag første” eller ”Gentag sidste” på skærmen. Din opgave er så at gentage det første eller det sidste ord i hver sætning. Du skal desuden forsøge at gentage ordene i den rigtige rækkefølge.

Antallet af sætninger vil øges, efterhånden som testen skrider fremad, hvilket gør, at det bliver sværere og sværere. Gør det så godt du kan.

Du skal altså:

- Læse sætningen højt for dig selv.
- Svare ”JA” eller ”NEJ” efter hver sætning.
- Gentage det første eller sidste ord i hver sætning. Når der står ”Gentag første” eller ”Gentag sidste” på skærmen. Forsøg at gentage ordene i den rigtige rækkefølge.”

Eksempel:

Sætning

TOGET SANG SANGEN
KAPTAJNEN SEJLEDE VÆK
FLASKEN GRINEDE HØJT

Gentag første

TOGET
KAPTAJNEN
FLASKEN

eller

Svar:

”Nej”
”Ja”
”Nej”

Gentag sidste:

SANGEN
VÆK
HØJT

Appendix 4: Model of Speechreading Benefit versus Delay

Written by: Søren Laugesen, Oticon Research Centre, Eriksholm

It is assumed that the relation between benefit of speechreading and delay in the hearing aid can be described by a function similar to a standard discrimination function (Brand, 1969). Compared to the discrimination function proposed by Brand, the present function is augmented with flexible range (y_R) and offset (y_{50}) parameters. Thus

$$y(x) = y_R \left(\frac{1}{1 + \exp(4s_{50}(x_{50} - x))} - \frac{1}{2} \right) + y_{50},$$

where x_{50} is the x -value at the midpoint of the curve and s_{50} is the slope of the curve at the midpoint. These parameters are illustrated in Figure A.1 below.

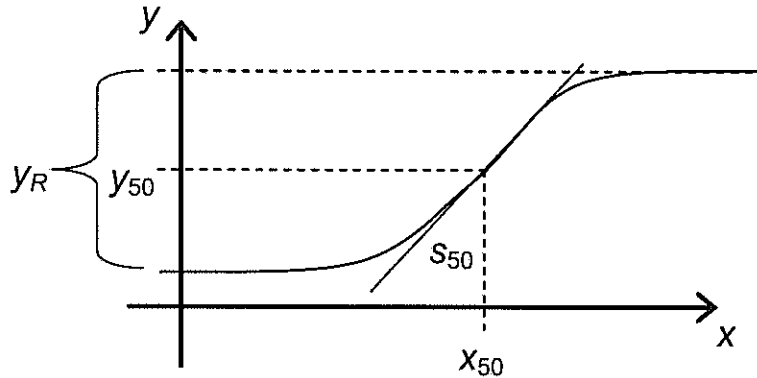


Figure 22. The generator function used to describe the relation between speechreading benefit and delay in the hearing aid.

For each subject a specific generator function is determined as follows. It turns out that the time delays are best viewed on a logarithmic scale, and hence the delay data are first transformed by the natural logarithm. Two test conditions need special treatment. These are the 0 delay condition, which is assigned the time value of 1 ms, and the audio only condition, which is assigned the time value of 2000 ms. Assume now that a total of M corresponding values of time delay d_m and JFC threshold t_m have been determined. The parameters of the generator function are then determined in a least-squares optimisation problem, which is formulated mathematically as

$$\min_{x_{50}, s_{50}, y_{50}, y_R} \left\{ \sum_{m=1}^M \left[t_m - \left(y_R \left(\frac{1}{1 + \exp(4s_{50}(x_{50} - \ln d_m))} - \frac{1}{2} \right) + y_{50} \right) \right]^2 \right\}.$$

From each subject-specific generator function a critical delay is then determined as the delay at which the predicted JFC threshold has increased by Δt ($= 1$ dB). Thus, the critical delay d_c is found from

$$y_R \left(\frac{1}{1 + \exp(4s_{50}(x_{50} - \ln d_C))} - \frac{1}{2} \right) + y_{50} = y_{50} - \frac{1}{2} y_R + \Delta t \Rightarrow$$

$$d_C = \exp \left(x_{50} - \frac{1}{4s_{50}} \ln \left(\frac{y_R}{\Delta t} - 1 \right) \right).$$

The fitting of the generator function and the determination of the critical delay requires that the delay versus JFC threshold data actually behave according to the assumptions. This turned out to be the case for the majority of test subjects; successful examples are shown in Figure A.2.

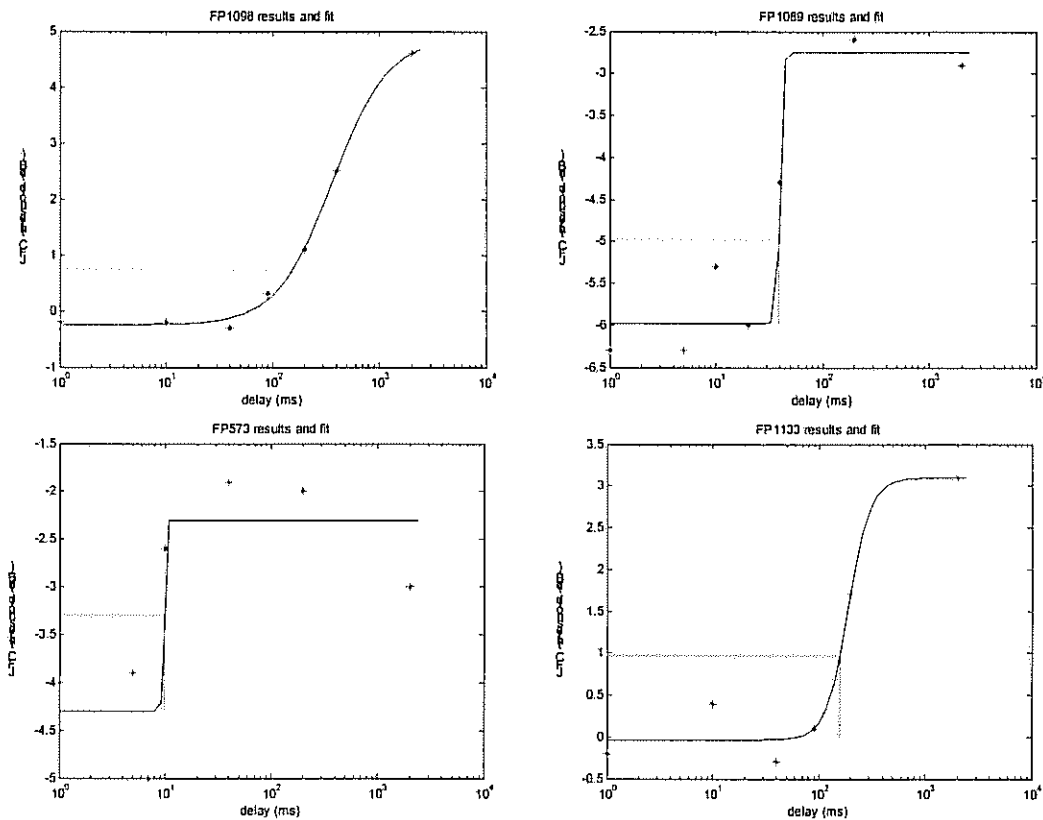


Figure 23. Results of fitting the generator function to measured data in four successful cases. The critical delay is also indicated in each case.

Appendix 5: Supplementary Tables and Plots

	Beta	Std.Err.of Beta	B	Std.Err.of Beta	t(19)	p-level
Intercept			4.188551	1.385365	3.023429	0.006989
PTA500Best/Aided	0.136903	0.227256	0.014264	0.023678	0.602417	0.554019

TABLE 11: SIMPLE LINEAR REGRESSION ANALYSIS OF CRITICAL DELAY/ HEARING LOSS

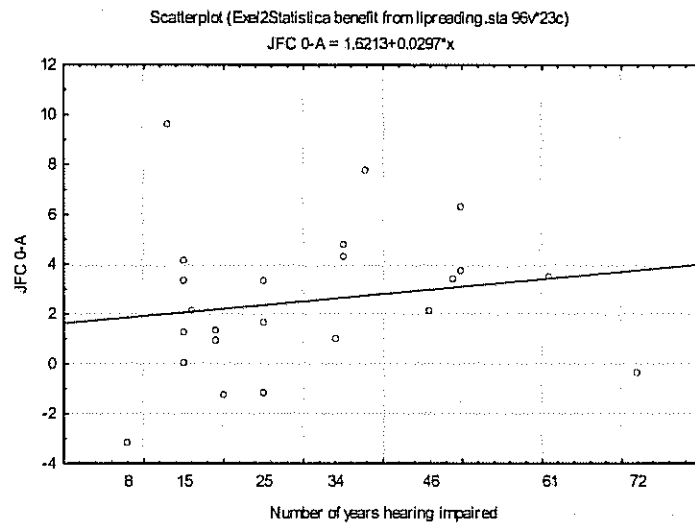


FIGURE 24: SIMPLE LINEAR REGRESSION ANALYSIS OF SPEECHREADING BENEFIT/NO OF YEARS HEARING IMPAIRED

	Beta	Std.Err.of Beta	B	Std.Err.of B	t(21)	p-level
Intercept			1.621265	1.279607	1.267002	0.219026
Years of hearing impairment	0.173764	0.214898	0.029730	0.036768	0.808588	0.427818

TABLE 12: SIMPLE LINEAR REGRESSION ANALYSIS OF SPEECHREADING BENEFIT/NO OF YEARS HEARING IMPAIRED

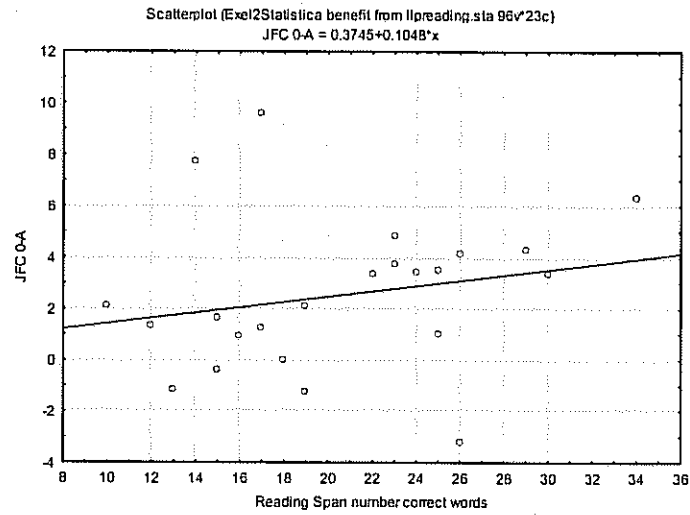


FIGURE 25: SIMPLE LINEAR REGRESSION ANALYSIS OF SPEECHREADING BENEFIT/READING SPAN SCORE

	Beta	Std.Err.of Beta	B	Std.Err.of B	t(21)	p-level
Intercept			0.374505	2.140207	0.174985	0.862767
Reading Span, correct words	0.223236	0.212711	0.104844	0.099901	1.049479	0.305886

TABLE 13: SIMPLE LINEAR REGRESSION ANALYSIS OF SPEECHREADING BENEFIT/READING SPAN SCORE