# Audibility of amplitude and phase changes in a wideband signal

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# Audibility of Amplitude and Phase Changes in a Wideband Signal

H. Perquin

# Audibility of Amplitude and Phase Changes in a Wideband Signal

Report of Practical Work at the
Institute for Perception Research
in Partial Fulfilment of the Requirements for
the Degree of Master of Technical Physics
July 1991

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# Audibility of
# Amplitude and Phase Changes
# in a Wideband Signal

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July 1991

# SAMENVATTING

Het menselijk oor is niet perfect, in die zin, dat bepaalde geluiden niet gehoord zullen worden als er andere geluiden aanwezig zijn. Dit effect heet maskering van geluid. Een geluid dat een ander geluid maskeerd heet de masker, het geluid dat door de masker gemaskeerd wordt (en dus niet waargenomen wordt) heet de maskee. Er zijn verschillende typen van maskering. Gelijktijdig (simultaneous) maskeren komt voor als beide geluiden gelijktijdig aanwezig zijn. Een bekend voorbeeld van gelijktijdig maskeren is het toon op toon maskerings experiment. Een sinusvormige geluidsgolf (de masker) is in staat om een geluidsgolf van een andere frequentie te maskeren (de maskee), de maskee wordt dus niet waargenomen terwijl hij wel in het signaal aanwezig is. Andere types van maskering zijn, voorwaards en terugwaards (forward and backward) maskeren, en komen respectivelijk voor als de masker in de tijd voor de maskee komt en omgekeerd. Een bekend voorbeeld hiervan is het maskeren van een impuls door een andere impuls.

In dit experiment werd onderzocht hoe maskering afhangt van fase en amplitude. Hiertoe werden de maskee detectiegrenzen met behulp van een twee-interval geforceerde keuze procedure (two-interval forced choice) bepaald voor verschillende proefpersonen. Als masker werd een periodieke impuls gebruikt met een herhalings frequentie van 100, 200 en 400 Hz. De maskee bestond uit een amplitude gemoduleerde sinus, waarvan het maximum amplitude ofwel samenviel met de impulsen (het symmetrische geval), ofwel in tegenfase was met de impulsen (het antisymmetrische geval). De masker werd aangeboden op 70 of 80 dB SPL.

Op grond van eerdere experimenten op dit gebied werd verwacht dat: (1) Voor hoge maskee frequenties is de symmetrische maskee moeilijker te detecteren dan de antisymmetrische. (2) Voor lage maskee frequenties zijn beide typen even goed te detecteren. (3) De detecteerbaarheid van beide maskee typen wordt beter als de maskee frequentie verhoogd wordt. (4) Door het verhogen van de herhalings frequentie van de impulsen zal het moeilijker worden om de maskee te detecteren.

De resultaten van de experimenten vertonen wat betreft de experimenten gedaan voor een herhalings frequentie van 100 Hz goede overeenstemming met de verwachtingen. Resultaten voor hogere herhalings frequenties bleken echter niet zonder meer als overeenstemmend geinterpeteerd te kunnen worden. Reden hiervoor kan zijn dat door de grotere moeilijkheid die testpersonen ondervonden bij het luisteren naar deze stimuli ook grotere fouten gemaakt werden.

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# INTRODUCTION

The human auditory system can analyze sounds in a way similar to Fourier analysis. However, it has a limited frequency selectivity and functions as a group of bandpass filters, covering the whole auditory frequency range from 20 Hz to 20 kHz. The critical bandwidth of these filters increases as the frequency increases. Therefore the best frequency resolution of the auditory system is found in the low frequency region. On the other hand this means that the amplitude of the impulse response of a filter at high frequencies decays faster than at low frequencies, the temporal resolution is better in the high frequency region.

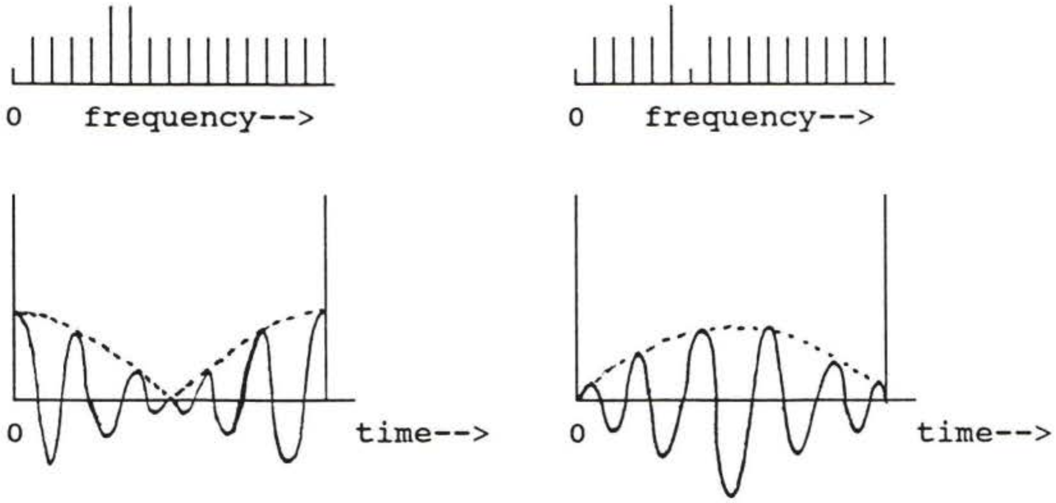
Another phenomenon observed in previous experiments (Small, 1959; Raab, 1961) is that the threshold of detectability of one sound can be increased by the presentation of an other sound. This phenomenon is called masking. We define a masker as a sound which is able to increase the detection threshold of another sound, this other sound is called the maskee.

There are several types of masking. Simultaneous masking is a phenomenon which occurs when two sounds are present at the same time. The simplest and most explored form of this masking type is the pure tone on pure tone masking. Two sinusoidal waveforms of different frequency are presented to the subject, one tone is reduced in intensity until it becomes inaudible. Now, the tone is masked by the other tone.

Other types of masking are forward and backward masking. Forward masking occurs when a sound is masked by another sound which preceded the masked sound in time. Backward masking works the other way around, the maskee precedes the masker. An example of these types of making is the masking effect of an impulse masker (acoustic click) on an impulse maskee which is presented just before or just after the masker.

More and more evidence is collected that the temporal waveform of the masker (phase change of the masker) play an important role in masking another sound.

The aim of this experiment is to investigate the influences of a temporal change in the masking waveform on the detection threshold of another sound. We use a periodic impulse as masker. We define the fundamental frequency as the repetition frequency of the impulses. In the experiments we will use 100, 200 and 400 Hz as fundamental frequencies. The periodic impulses are created by adding up equal amplitude harmonics of fundamental frequency of the impulse in the same phase. As maskee (the sound to be masked) we use a sine that is amplitude modulated with the fundamental frequency of the impulses, the maskee is created by adding up two successive harmonics. The total stimulus can be created by increasing two successive harmonics of the fundamental frequency, thus creating a stimulus with a periodic impulse and with superimposed the amplitude modulated maskee with its maximum amplitude at the impulses. Another way to create a stimulus is to increase one harmonic and decrease the next, creating a stimulus with maskee amplitude maximums in between the impulses. We define these two types of stimuli as: symmetric and antisymmetric (fig.1).



*(a)* *(b)*

*Fig. 1. Time pattern of the Stimuli and their Fourier spectrum, (a) symmetic, (b) antisymmetric.*

We expect the masking effects of the periodic impulses to consist out of forward and backward masking. Because of the filter bank function of the auditory system the 'ringing' time will decrease as frequency increases, therefore the higher pitched maskers should be better audible. We expect this type of masking to occur at high frequencies of the maskee. At low frequencies we expect that the hearing system is not able to track the stimulus in a temporal way.

Consequently, if these expectations are true, we expect the following results from the experiments:

(1) The symmetric stimuli have higher maskee detection thresholds than the antisymmetric stimuli in the high frequency region.

(2) The maskee detection threshold of both types of stimuli will become lower as the frequency increases.

(3) In the low frequency region the threshold are almost the same for both types of stimuli.

(4) As the fundamental frequency of the periodic impulse increases, the threshold in the high frequency region will increase for both stimuli.

The literature about the hearing system is extensive, I found the book of Gelfand (1990) and an article of Schroeder (1975) useful for a first exploration of the field.

The ear is divided in three areas, the outer, middle, and inner ear. The outer ear consists of the pinna (auricle) and the ear canal (external auditory meatus). The pinna is the external appendage of the ear. It serves as a sort of horn. Sounds from different directions are transported to the ear canal with different frequency transfer functions, thus making it possible to detect the direction from where the sound comes. The pinna also serves as protection for the ear canal. The ear canal terminates at the eardrum, it is about 2.5 cm in length and 0.7 cm in diameter. It's surface is covered with ceruminous (wax) and sebaceous (oil) glands to lubricate it and to keep it free of foreign objects. Tiny hears also help to protect the ear from invasion.

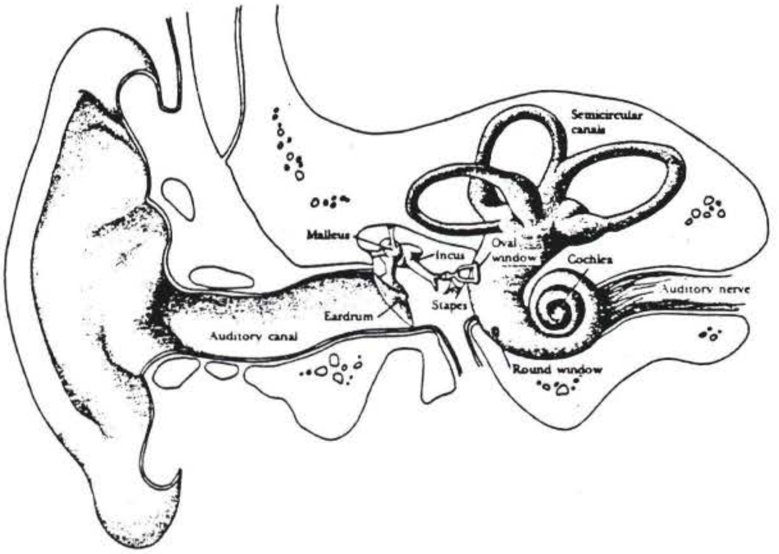


*Fig.2. Anatomy of the hearing system.*

The eardrum (tympanic membrane) marks the beginning of the middle ear. The membrane is quite thin (approx. 0.074 mm) and about 0.9 cm in diameter. The eardrum is connected by the ossicular chain, consisting of three little bones: mallus (hammer), incus (anvil) and staples (stirrup), which transfer the sound wave from the eardrum to the cochlea. The tiny bones are connected by two muscles. At high sound intensities, mobility of the bones is reduced by involuntary tensing of muscles attached to the bones (acoustic reflex) thereby protecting delicate inner-ear from overload damage. The ossicular chain resides in the middle ear cavity (tympanum) which is connected by the Eustachian (auditory) tube to the nasopharynx in order to keep air pressure equal on both sides of the eardrum.

The inner ear structures are contained in a system of spaces and canals, the osseous labyrinth. These spaces and canals are grossly divided into three sections: the vestibule, the cochlea, and the semicircular canals. The semicircular canals are used for balance and are therefore of no direct interest to us. In the vestibule there is a oval window which accepts the stapedial footplate. Sound energy is tranfered trough the vestibule to the cochlea. The cochlea is a snail shaped organ in which the incoming sounds waves are transformed in outgoing nerve spikes. The cochlea is divided into three fluid-filled channels. Two of these channels are separated by the basilar membrane which supports the organ of Corti where the actual mechanical to neural transduction is effected by the hair cells. The first to ascribe the frequency selective properties to the basilar membrane was Helmholtz who visualized it as a succession of tuned string (as in a piano) resonant at different frequencies. However, when Von Békésy actually looked through his microscope at the basilar membrane under acoustic stimulation he saw travelling (with decreasing velocity) waves from the staples at the base of cochlea to the helocitrema at the apex about 35 mm from the stapes. The envelope of these travelling waves varies with frequency, the lower the frequency the farther the wave travels before resonance and attenuation. The haircells triggered by the motion of the basilar membrane transfer the information about the frequency and amplitude of the stimulus to the brain. The basilar membrane acts as a frequency discriminator, the dependence of the bandwidth is shown in fig.3.

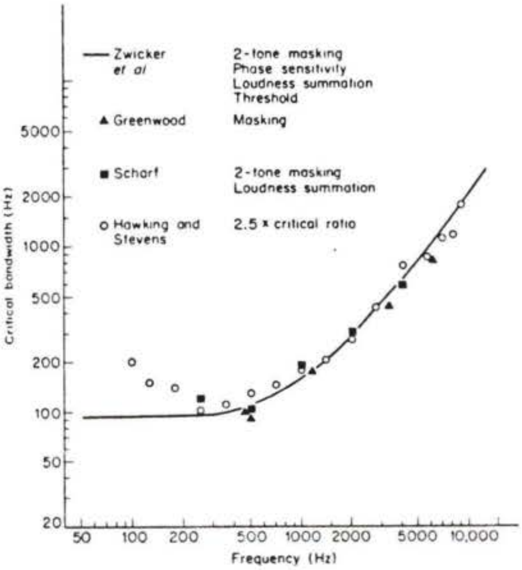


*Fig.3. Bandwidth of the auditory filter bank as function of the frequency.*

Speech is an important class of signals that serves as input to the auditory system and it contains many frequency components. As we know, speech sounds have a enormous amount of variation in terms of its representation of Fourier analysis. Even for one sample of the sounds there are almost infinitive ways to manipulate it's spectrum. However, it is not necessary to experiment in that way, since the rules governing the function of the system can be investigated by using simple stimuli with the characteristics relevant to our goals. Our aim is to investigate the influences of waveform changes on the masking threshold of the other sounds. Any amplitude or phase changes in the components cause a change in the temporal waveform. The threshold of these changes will be investigated.

A definition of masking could be: the raise in perception threshold of one signal caused by the presents of an other signal. An example of everyday live is turning on the car-radio to eliminate the noise made by the car, the sounds of the radio are said to mask the noise of the car. The signal to be masked is called the maskee, the signal which maskes the maskee the masker.

Many experiments were done on tone-on-tone masking (Small, 1959; Ehmer, 1959), the masking effect of one sine on an other simultaneous sine. This type of experiment examines the so called simultaneous masking effects, the masker and maskee are present at the same time. Typical results are given in fig.4, this is an experiment where the maskee is held at one frequency and the masker is scanned through the frequency range. The figure shows the threshold level of the masker, so that the maskee is just audible. We can see that the lowest masker thresholds occurs just around the frequency of the maskee. The distance maskee-masker greatly influences the masking capabilities. At frequencies below the maskee the masker threshold is relative low, at frequencies above the maskee frequency the masker threshold becomes relative high, it becomes even impossible to mask the maskee sine with a masker that has a higher frequency. Maximum masking occurs when the masker occupies about the same frequency region as the maskee, low tones mask high tones more easily than the reverse, at least at high intensities.

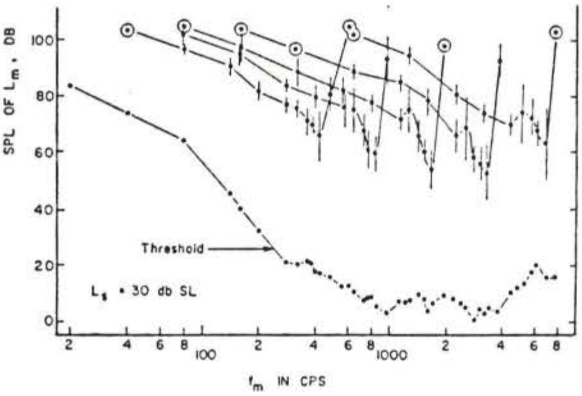


*Fig.4. Tone-on-tone masking, masker thresholds.*

Except for simultaneous masking there are forward and backward masking effects, which for instance occur around acoustic clicks (impulses). An example is the work of Raab (1961), who studied the masking effect of a click on another click displaced a little in time. His results show that the backward masking effect, the maskee proceeds the masker click in time, is less evident as the forward masking effect (fig.5).

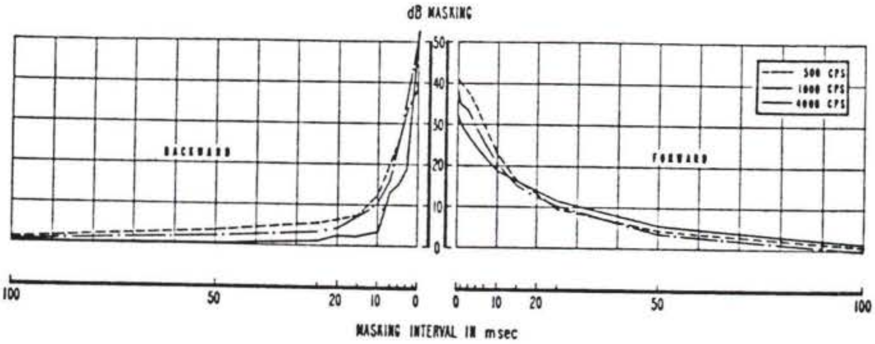


*Fig.5. Maskee threshold levels by temporal masking of an impulse by an impulse.*

Duifhuis (1970a, 1970b, 1973) also did research on the masking effect of clicks. His second 1970 article deals with the masking of periodic sine wave burst by clicks. This experiment looks very much alike with the experiments done here, so we will give it a closer look. Duifhuis used a sine wave burst of 8 cycles as a maskee, the masker was a periodic impulse with a repetition frequency between 25 and 400 Hz. The choice for a 8 cycle sine was a compromise, the burst had to be small in comparison to the period time between two impulses in order to get a good time resolution, it had to be long in order to get a good frequency resolution. The position of the maskee burst was swept between two impulses, and the threshold measured. Some of his results are given in figure 6.

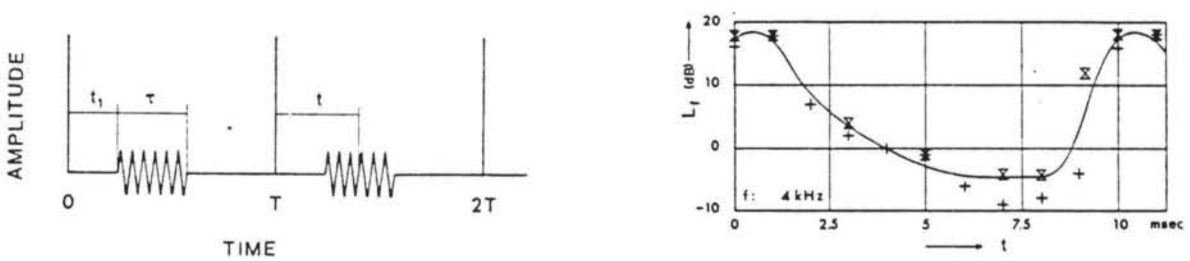


*Fig.6. Time pattern of the stimulus used by Duifhuis and his results for identification threshold for this stimulus.*

However there are some differences which make it difficult to compare the data of Duifhuis with the data from the experiments done here. First, the envelope of the maskee is different, second, Duifhuis measured at a sensation level 50 dB whereas this experiment was done at sound pressure levels of 70 and 80 dB, and third, Duifhuis measured identification thresholds whereas we measured thresholds of audibility. If we are only interested in differences in threshold level of the symmetric and antisymmetric case and assume that different sound pressure levels and different methods for measuring the threshold only affect the absolute scale of the measurements, we could compare data. However we still have the problem of different envelopes.

We could try to add up the maskees of Duifhuis' envelope in order to get the envelope we used, and compute in this way the difference between the symmetrical and antisymmetrical maskers. The question is of course whether if we add up two maskers of same intensity the masked threshold would also be raised by 3 dB, in that case it would be linear. Green (1967) did research in this area, he experimented with the addivity of tone-on-tone maskers and noise-on-tone maskers. He found in almost all cases a threshold shift of about 9-12 dB, far greater than the 3 dB expected from the linear model. However a more recent report was made by Moore (1985), who did the same additivity experiments. He concluded that the 'excess' masking can be explained in terms of combination tones and the use of different detection clues for the single maskers and for the masked pairs. In a experiment he showed that by minimizing the possibility of combination tones the 'excess' was only 3-5 dB. Taking this last argument in account we try to add up the Duifhuis' results for 100 Hz fundamental frequency.

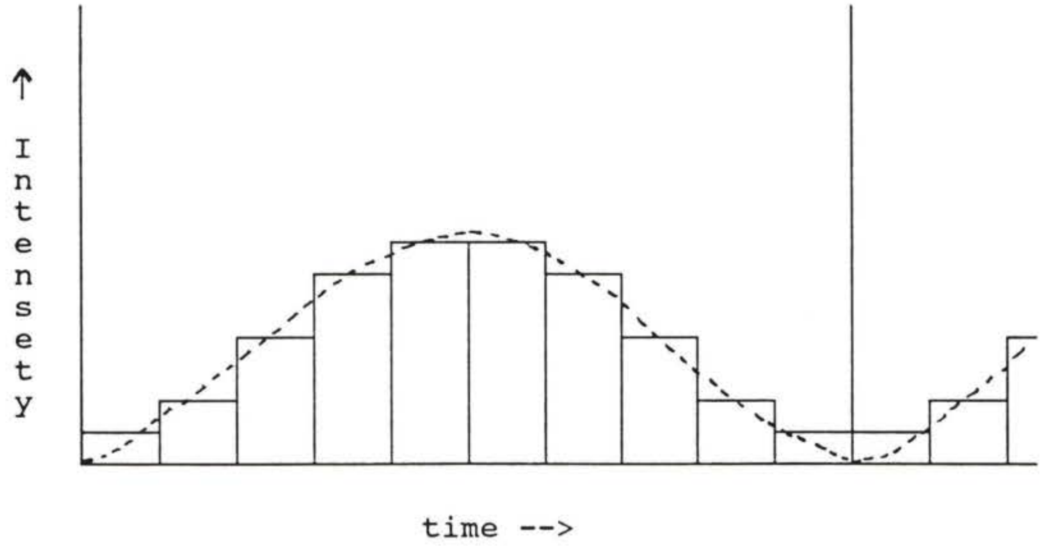


*Fig.7. Envelope of the experiment done here (dashed) and the envelope of the addition of ten Duifhuis' envelopes with proper weight factors (solid).*

Duifhuis measured his masking curves in about ten points for the time shift (fig.6) of the maskee relative to the impulse. We use a ten point estimate to produce our envelope, we calculate a envelope by adding up ten square 8 cycle bursts with proper weightfactors. The result of this addition is a waveform that resembles our waveform in such a way that the sound energy contained in each of the ten time intervals is equal to the energy contained in the same intervals of our waveform (fig.7). Now, by adding up the multiplications of the weightfactors with the thresholds values found by Duifhuis at the ten time intervals, we have a expectation threshold for our experiment. Results of these additions, as well the difference between the maximum and minimum of Duifhuis' masking curves, are given in Table I. From this table we see that we expect the difference to be 10 dB above 2 kHz.

*Table I. Threshold level difference between symmetric and antisymmetric calculated from Duifhuis' data.*

| Maskee frequency (kHz) | 2 | 4 | 8 |
|---|---|---|---|
| Peak to peak difference (dB) | 14 | 20 | 18 |
| Calculated difference (dB) | 5.4 | 9.7 | 10.7 |

Because of the increase of critical bandwidth of the auditory filters at higher frequencies (fig.3), will the frequency resolution decrease at higher frequencies, but the temporal resolution will increase. This means that a subject whose ears are tuned to a certain frequency and listens to a click, the click will produce a certain 'ringing' at the tuned frequency. The duration time of this ringing will decrease with increase of frequency (fig.8). If another (weak) sound is present at the same tuned frequency this sound will be masked by the click, because of the 'ringing' of the click (Duifhuis, 1970a). However if the frequency of this sine is increased the ringing time will decrease and the sine would be easier detectable. We therefore expect for this experiment that in the high frequency region the higher frequencies have lower detection threshold as lower frequencies.

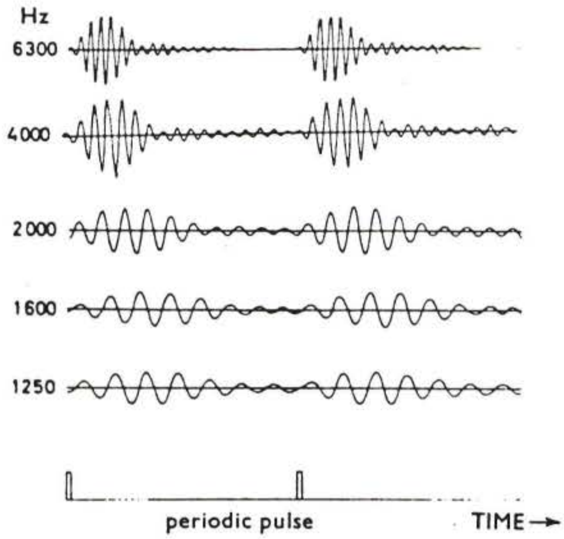


*Fig.8. Ringing of an impuls illustrated. The higher the frequency gets the shorter is the ringing time.*

In low frequency region the ringing of the pulses is so long in time, that we expect the hearing system to detect the sine not in a temporal way but using frequency selectivity of the filter. If so, then the auditory system would be unable to track phase changes, the detection thresholds for both type of stimuli would be the same.

If we increase the repetition time of the periodic impulse, we will also increase the amount of masking by the pulses. Now, the ringing has less chance to decay to a low value because before this happens a second pulse is produced. The expectation is therefore that if we increase the fundamental frequency of the impulses we will also measure a increase in detection threshold.

## METHOD

### 1. Stimuli

There are basically two ways to create the required stimuli. The first is to generate the waveform with a pulse generator (Duifhuis, 1970a). The second is to compute the waveform from its Fourier spectrum and present it via a Digital to Analogue Converter (DAC). We chose the second option.

All stimuli were computed on a VAX-system by adding the harmonics of the fundamental frequency upto 10 kHz, with a sampling frequency of 20 kHz and a resolution of 16 bits. Just after the DAC there was a programmable lowpass filter which was programmed to cutoff at 7.8 kHz, this was done to eliminate aliasing noise. Symmetric stimuli were created by increasing two successive harmonics of the fundamental frequency, antisymmetric ones by increasing one harmonic and decreasing the next. After computing the stimuli they were stored to disk for later use. The power of the maskee was measured relative to the power of one masker harmonic, a 0 dB maskee level corresponded to a maskee with both sine components equal in size compared to a harmonic of the masker, thus for the symmetric case the spectrum of the whole stimuli (maskee and masker) contained two successive harmonics doubled in size, and the antisymmetric case contained a doubled harmonic with the next harmonic missing. For the fundamental frequency of 100 Hz were created: 21 files for maskee levels from 0 to -40 dB, and a reference file containing only the masker. For the other two fundamental frequencies 24 files for maskee levels from 10 to -36 dB, and a reference file were created. These frequencies started with a 10 dB maskee level because the maskee was more difficult to hear than in the 100 Hz case.

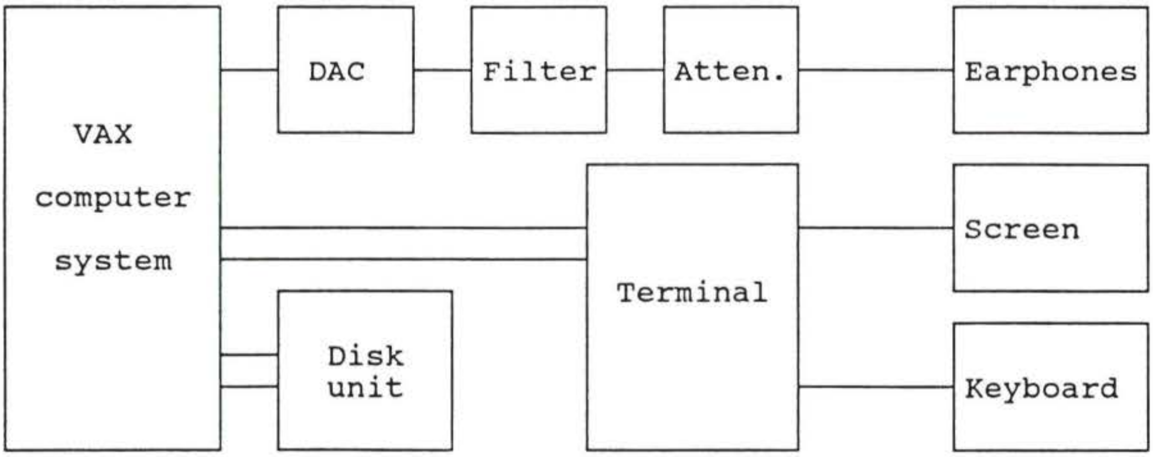


*Fig.9. Experimental setup.*

The stimuli were presented to the subject via a 16-bit DAC coupled to a Philips

PM 5175 amplifier (set at -6 dB) to modify the input impedance then through a variable attenuator (Daven 30 x 2 dB) and finally through Etymotic Research ER-2 earphones using Etymotic Research ER1-14 eartips (fig.9). The sound pressure level was measured at the earphones, and was set to 70 or 80 dB SPL for use in these experiments. The experiments were performed in a acoustically isolated environment. The subject responded at the stimuli using the keyboard of a terminal when asked to do so on the terminal screen. A interactive computer program running on this terminal presented the stimuli, collected the responses and computed the averages and standard deviations.

## 2. Procedure

The procedure used to find the threshold values was a two alternative forced choice (2AFC) adaptive procedure (Levitt, 1971; Schlauch and Rose, 1990). This type of procedure was used because it produces stable data and it is efficient. The subject was presented two stimuli with a duration of 200 ms each and a 500 ms pause in between. The 200 ms duration of the stimuli was sufficiently long to reach a stable sound pressure level (Plomp, 1964). The 500 ms pause in between the stimuli turned out to be the best choice for this parameter, a longer pause did not decrease the threshold levels, a shorter pause was not used because it gave the subjects the impression of being in a hurry (Table II).

*Table II. Relation between threshold in dB and the length of the pause interval at several frequencies of the maskee.*

| Maskee frequency (kHz) | 1 | 2 | 4 | Mean |
|---|---|---|---|---|
| 300 ms pause interval | 15.6 | 17.6 | 20.7 | 18.0 |
| 500 ms pause interval | 14.8 | 18.8 | 19.5 | 17.7 |
| 750 ms pause interval | 14.9 | 15.5 | 21.4 | 17.3 |

The stimuli were ramped at the beginning and at the ending with a sine function of 20 ms duration. Fig.10 illustrates the presented stimuli. Before the stimuli are presented the screen is refreshed, this was important for measuring the absolute threshold where one of the stimuli was a silent interval, looking at the screen the subject could decide wether he heart the silent interval first or second. One stimulus contains the masker with the maskee, the other only the masker. The two stimuli are randomly ordered by the computer, so there is no way for the subject to predict which stimulus contains the maskee. Then the subject is asked which stimulus contains the maskee. The first time the stimuli are presented the amplitude of the maskee is relatively high to enable the subject to hear the difference clearly and make a correct choice. If the answer was correct then the stimuli are once more presented with the same amplitude of the maskee. After two correct answers in a row the amplitude of the maskee is lowered, and again the subject is asked to distinguish between the two stimuli. The lowering of the amplitude of the maskee continues until the subject gives a incorrect response, then the amplitude is raised and the computer records the amplitude value where the incorrect response occurred as the first reversal. The computer will continue to increase the amplitude until two correct responses in a row occur, and thus marking the second reversal. So in general, the amplitude of the maskee is decreased after two correct responses and increased after a incorrect response or a correct response followed by an incorrect one. The computer presents stimuli in this way until 13 reversals occurred. Then the computer calculates the 4 midpoints of the last 8 reversals. A midpoint is the average of two successive turning points. Then it calculates the average and standard deviation of these midpoints. If the standard deviation of the midpoints is smaller than 3 dB the test is accepted and the responses are saved to disk for later interpretation, if not then the test is repeated until the standard deviation is within bounds. The average value computed in this way corresponds to the amplitude of the maskee at which 71% correct responses were given (Levitt, 1971).

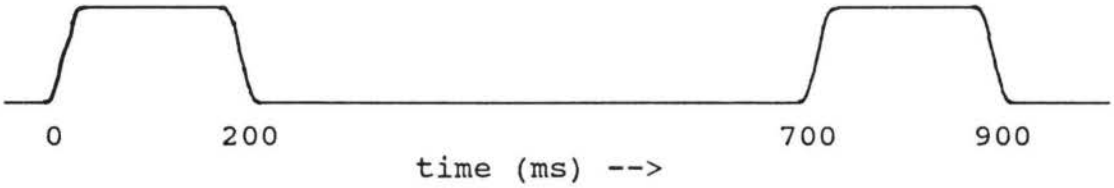


*Fig.10. Illustration of the structure of a single trail in the two-alternative forced-choice task.*

The difference between two amplitudes is 2 dB. In order to speed up the convergence to the end value of the threshold this difference is chosen greater at the beginning of a test. The difference is 8 dB before the first two reversals, 4 dB between reversal number 2 and 4. A typical test run looks as given in fig.11. In order to let the computer produce the requested stimuli quickly it was necessary to load all stimuli needed for the test into memory. The two stimuli used for one choice were 'glued' together in computer memory with a 500 ms silent interval in between, then it was send to the DAC as one stimulus. This was done, rather than sending the two stimuli separately to the DAC with a computer controlled pause in between, in order to keep the 500 ms pause as accurate as possible.

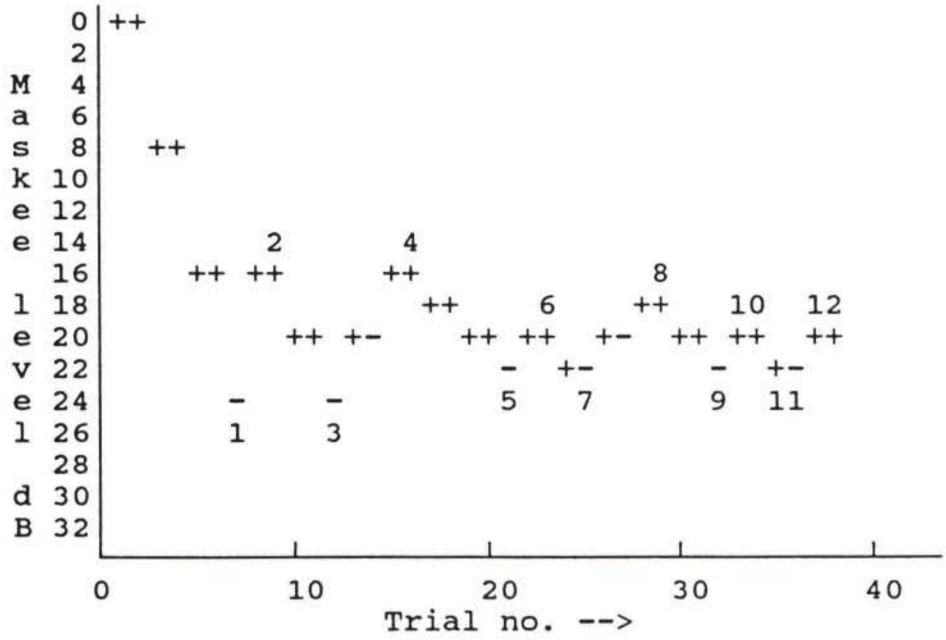


*Fig.11. Typical testrun. A plus-sign (+) indicates a correct response, a minus sign (-) a incorrect response by the subject, the reversals are numbered from 1 to 12.*

Using this procedure it takes approximately 3 minutes to conclude a test for one frequency of the maskee, thus a test for one frequency of the masker takes up about 20 minutes. The time required to conclude the whole experiment for three fundamental frequencies, two types of stimuli and two sound pressure levels is about 4 hours. A subject is able to do about two testruns on a visit, longer testing causes tiredness, so a subject has to pay at least 6 visits to the experiment room to complete the whole experiment.

## RESULTS

The experiments were done on four subjects, the results of these experiments will be given for each subject separately. Three subjects (including the author) where students who were not experienced in doing psychoacoustical experiments. Several testruns were made on them before the actual data was collected, this was done to give them time to get used to procedure and to make it clear what differences in the stimuli were expected to be spotted.

### 1. Subject HP

### Absolute maskee threshold in quiet

The threshold level for the 100 Hz maskee was measured. The results are given in fig.12. The curve is similar to a single tone threshold curve (Small, 1959).

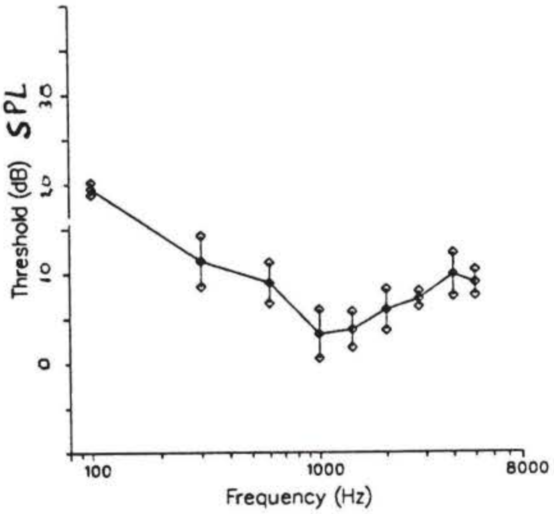
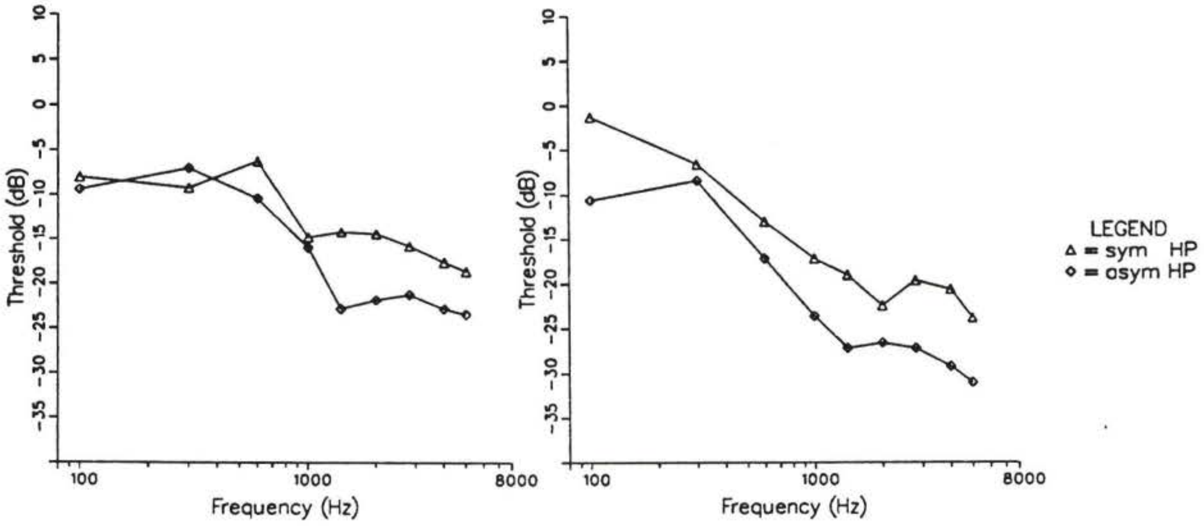


*Fig.12. Absolute threshold in quiet.*

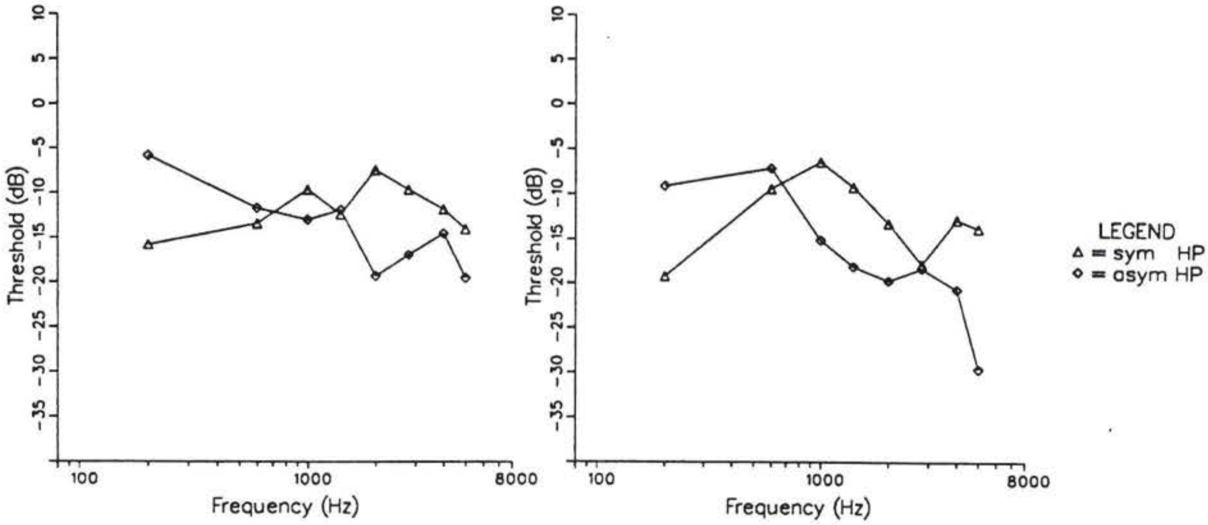
Fundamental frequency 100 Hz

The 100 Hz experiments show that the symmetrical maskee has approximately 7 dB higher detection threshold for frequencies above 1 kHz than the antisymmetrical one. For lower frequencies both graphs overlap. Above 1 kHz the threshold decreases with 2.5 dB/oct for all four graphs.



*(a)* *(b)*

*Fig.13. 100 Hz masker at 70 dB SPL (a) and 80 dB SPL (b).*

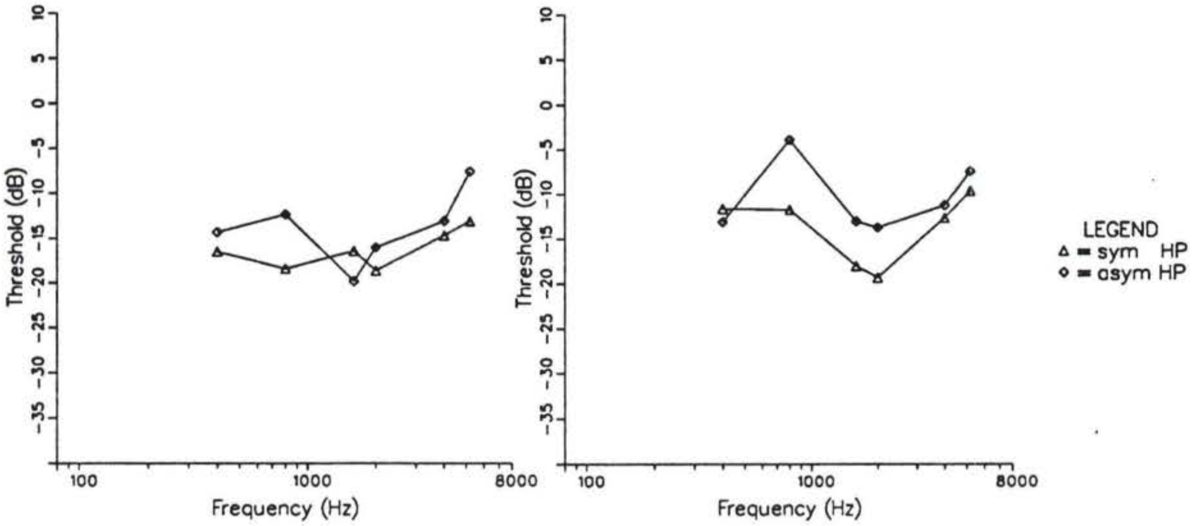


*(a)* *(b)*

*Fig.14. 200 Hz masker at 70 dB SPL (a) and 80 dB SPL (b).*

Fundamental frequency 200 Hz

Here again the symmetrical maskee threshold levels are above the antisymmetrical ones. Only now the distinction is less clear, in fig.15b the 2800 Hz points overlap. The threshold levels for lower frequencies are the same for both symmetries, looking at fig.15a they stay the same until 1400 Hz.



*(a)* *(b)*

*Fig.15. 400 Hz masker at 70 dB SPL (a) and 80 dB SPL (b).*

2. Subject EV

The threshold measurement, fig.16, shows that this subject has a 10 dB higher threshold below 1000 Hz.

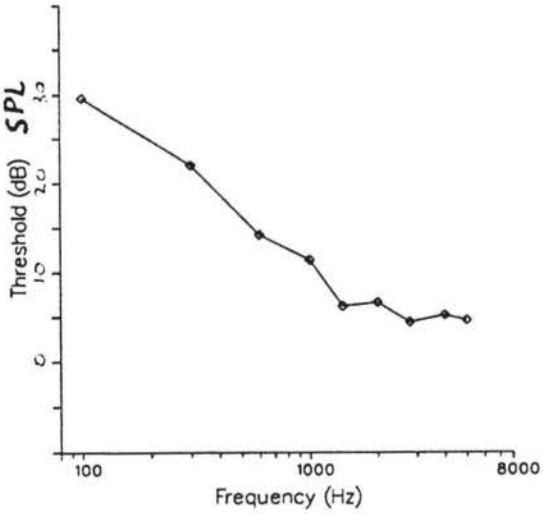
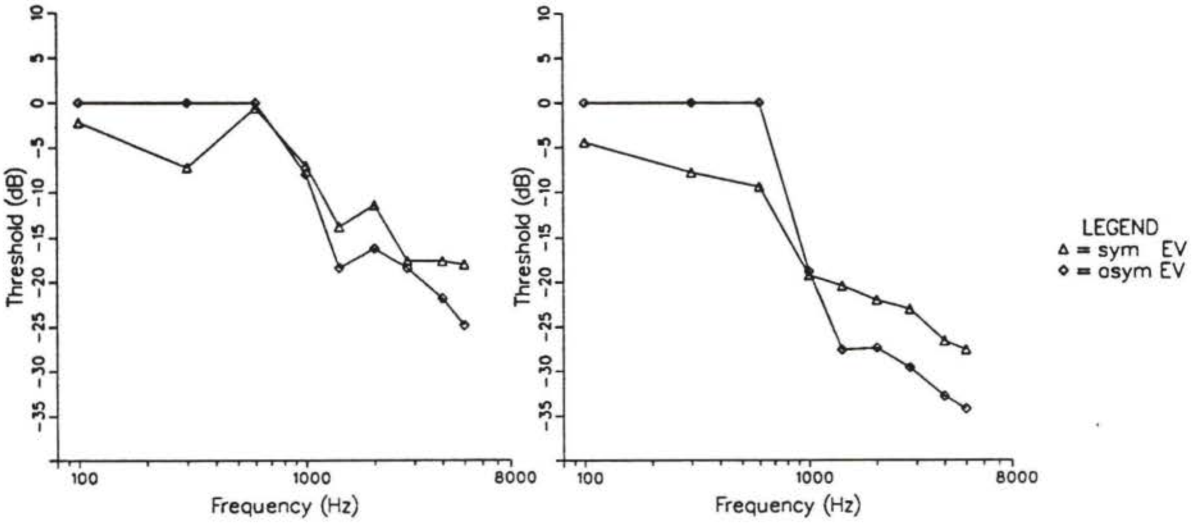


*Fig.16. Absolute threshold in quiet.*

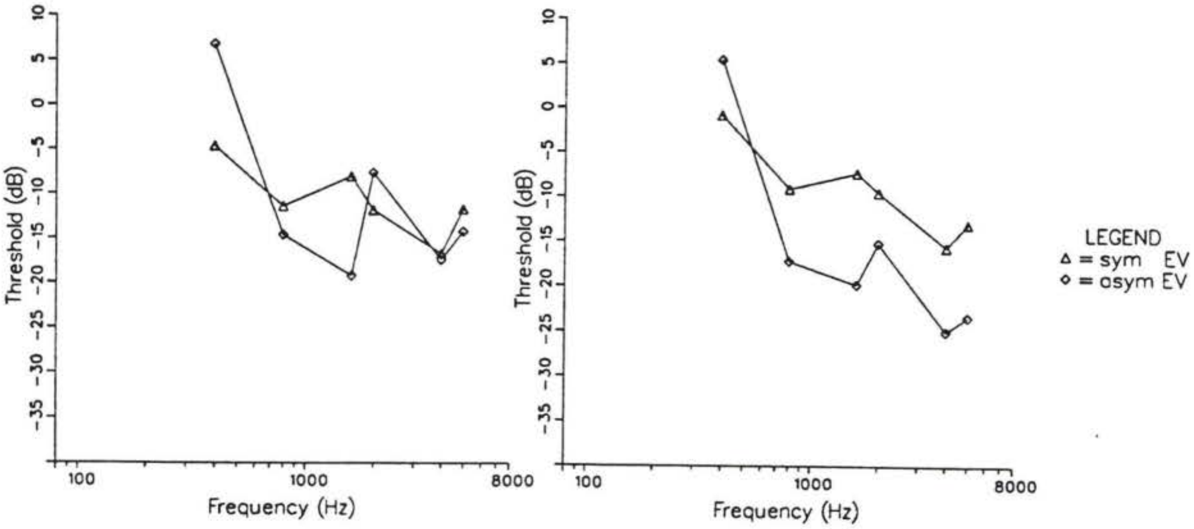
Fundamental frequency 100 Hz

Maskee frequencies below 1000 Hz were not be percepted by subject EV in the case of a symmetrical masker, they are plotted as 0 dB. Above 1000 Hz there is again a difference of 7 dB clearly observed in fig.17b, the slope is -3 dB/oct. Fig.17a. shows less distinction between the two types of stimuli, although the symmetrical maskee is still more difficult to hear.



*(a)* *(b)*

*Fig.17. 100 Hz masker at 70 dB SPL (a) and 80 dB SPL (b).*

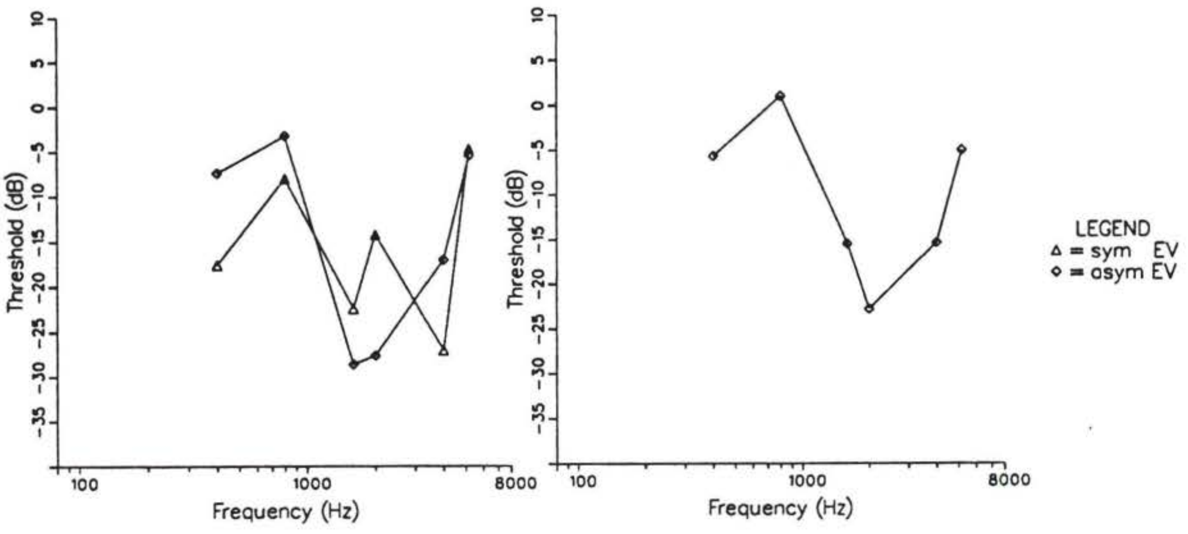


*(a)* *(b)*

*Fig.18. 200 Hz masker at 70 dB SPL (a) and 80 dB SPL (b).*

Fundamental frequency 200 Hz

Here again the difference between the two types of symmetries is not so clear for the 70 dB SPL case as for the 80 dB SPL case. For the 80 dB case, above 1000 Hz, the symmetrical type is 8 dB above the other type, the slope is -2.5 dB/oct.



(a) (b)

*Fig.19. 400 Hz masker at 70 dB SPL (a) and 80 dB SPL (b).*

3. Subject NCvD

This subject has a threshold that is overall about 8 dB higher, but for 4000 and 5000 Hz is it even 25 dB higher.

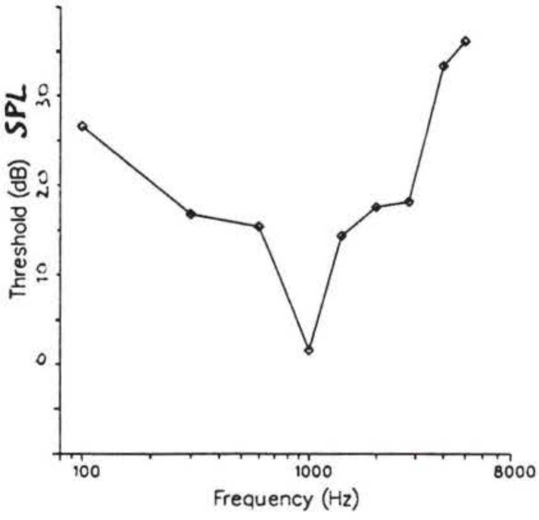
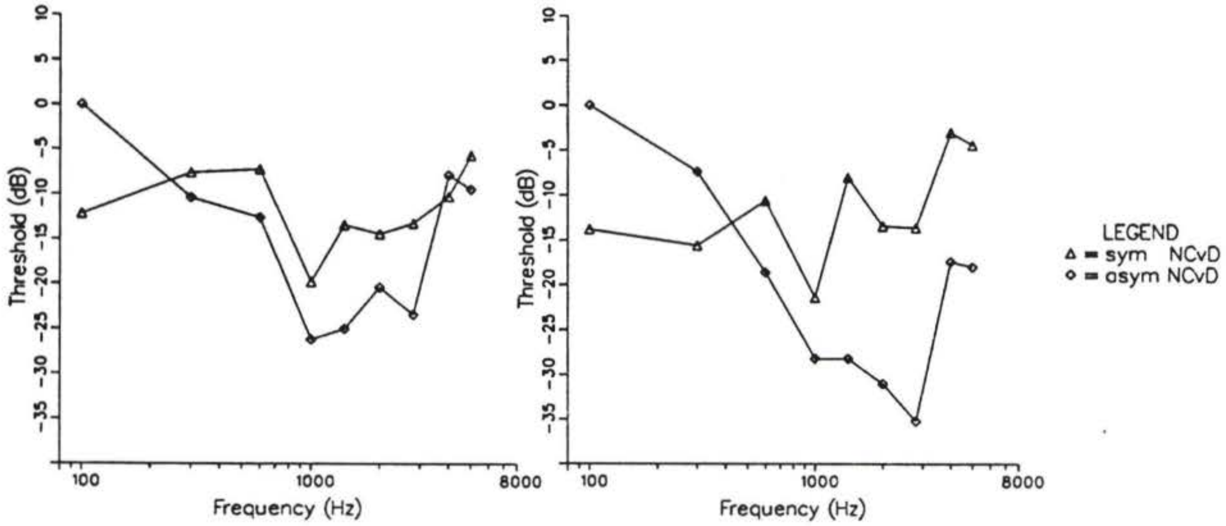


*Fig.20. Absolute threshold in quiet.*

Fundamental frequency 100 Hz

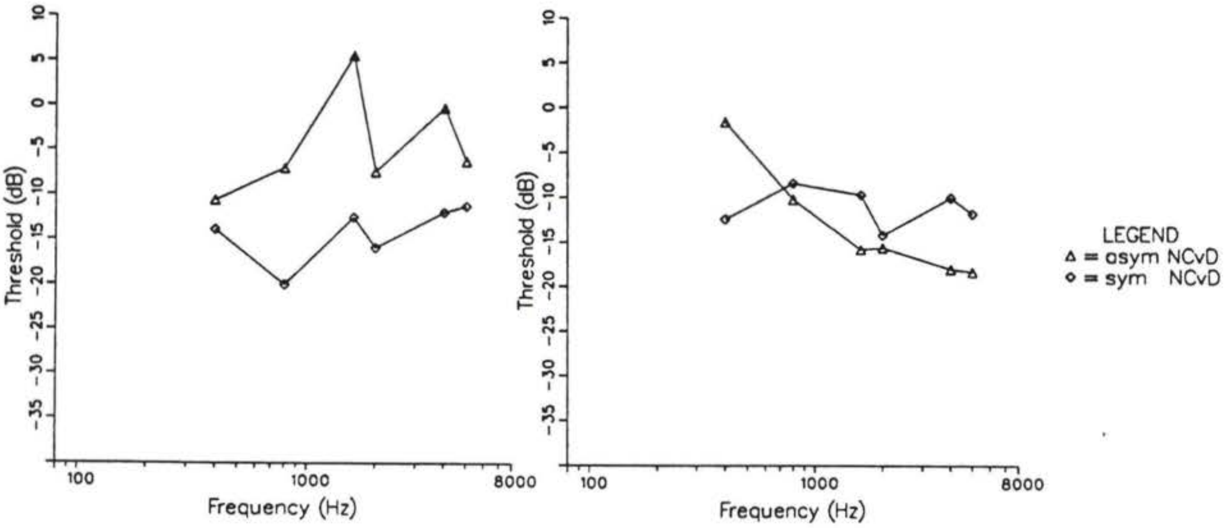
The bump at 4000 Hz mentioned above returns also in the 100 Hz experiments. Still, it is clear that the symmetric maskee detection threshold is higher. The two types of symmetries tend to divert as frequency increases.



(a)

(b)

*Fig.21. 100 Hz masker at 70 dB SPL (a) and 80 dB SPL (b).*



(a)

(b)

*Fig.22. 200 Hz masker at 70 dB SPL (a) and 80 dB SPL (b).*

Fundamental frequency 200 Hz

The 200 Hz experiments show no evident increase in threshold for high frequencies, it seems the 4000 Hz bump has vanished. The results for 80 dB SPL masker do not show a clear distinction between the two types. The 70 dB experiments however show at a difference of at least 7 dB between the two types.

400 Hz

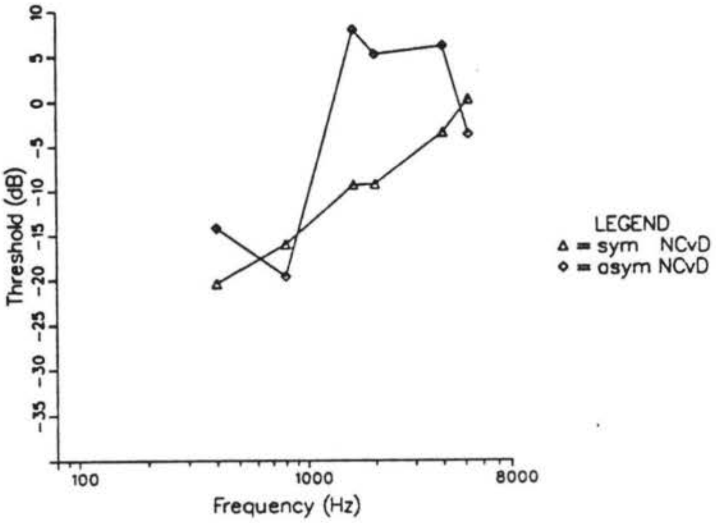


*Fig.23. 400 Hz masker 70 dB SPL.*

4. Subject CM

For this subject not all data was collected, but I would like to show it here because CM is the only subject of the four subjects used for these experiments who is experienced in doing psychoacousical experiments.

The subject has an absolute threshold curve which would be expected for a normal hearing subject.

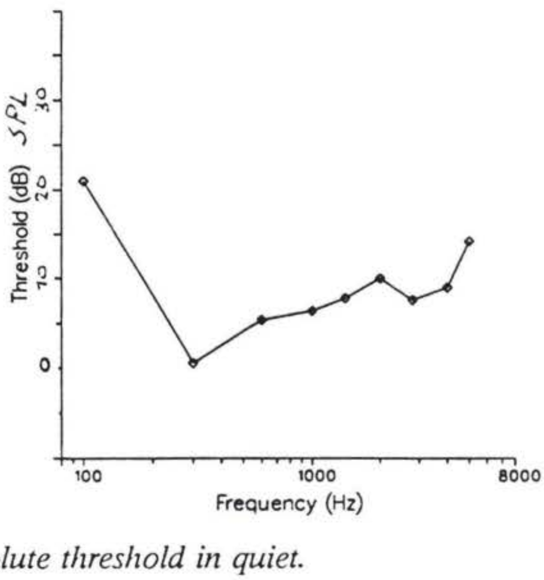


*Fig.24. Absolute threshold in quiet.*

## DISCUSSION

Because the data was collected for four subjects, we are able to average the data between the subjects and give standard deviations. However the data of subject NCvD is so different to the rest of the data that we decide not to use her data for averaging. The 100 Hz, 70 dB SPL antisymmetrical measurement was also done by two additional (unexperienced) subjects, their data and the data of the other subjects is used to produce fig.27. Examining these graphs we find a relatively large standard deviation in the low frequency region. I think this is because we used experienced subjects as well as unexperienced subjects. The more experience a subject has the better he hears the difference between these low frequency stimuli. I found this true for myself, I did the 100 Hz experiments a several times, the later experiments showed a better performance in the low frequency region. However I think it takes quite a long time to train. I tested subject EV, he did not hear the difference at all in some cases, again for this frequency region after he had completed the whole test and thus completed a reasonable amount of test hours. He still did not show any improvement.

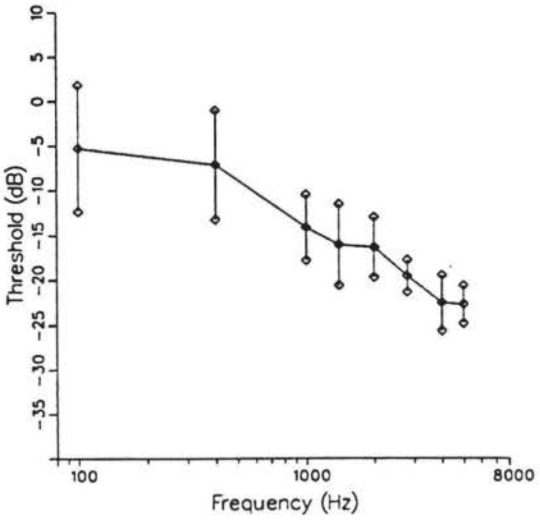
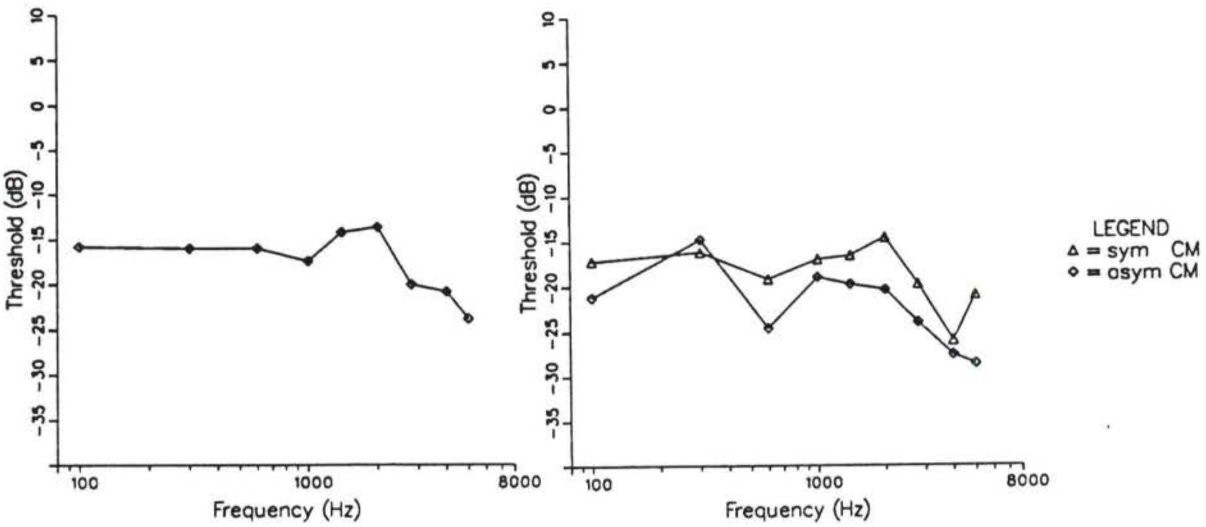


*Fig.27. Average of 5 subjects for 100 Hz fundamental at 70 dB SPL with a antisymmetric maskee.*

For the higher frequencies there is better correspondence of the data of the subjects. The standard deviations are so small that the standard deviation intervals of the symmetrical and the antisymmetrical case do not or just a little overlap. The symmetrical type of maskee has a detection threshold which is 7 dB higher than the antisymmetrical type. We expected from adding up square sine bursts that the difference would be 10 dB, although this expectation was based on rather crude arguments it produced a relatively well prediction of the difference. The slope of the high frequency curves is -3 dB/oct. This follows our expectation that the threshold becomes lower as the frequency increases.

Fundamental frequency 100 Hz

The data for this subject corresponds to the data of the other subjects for frequencies above 1000 Hz. At low frequencies the threshold is significant lower.



(a) (b)

*Fig.25. 200 Hz masker at 70 dB SPL (a) and 80 dB SPL (b).*

Fundamental frequency 200 Hz

Here it is the same as with 100 Hz, good comparison can be made with the other subjects for high frequencies, but low frequency thresholds are lower.

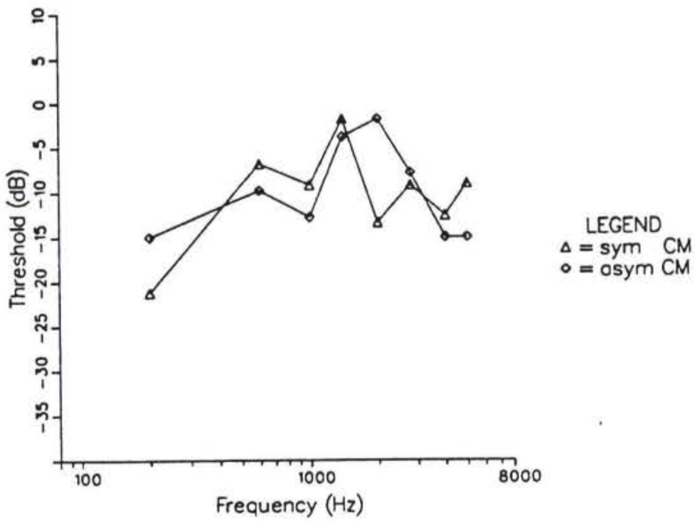
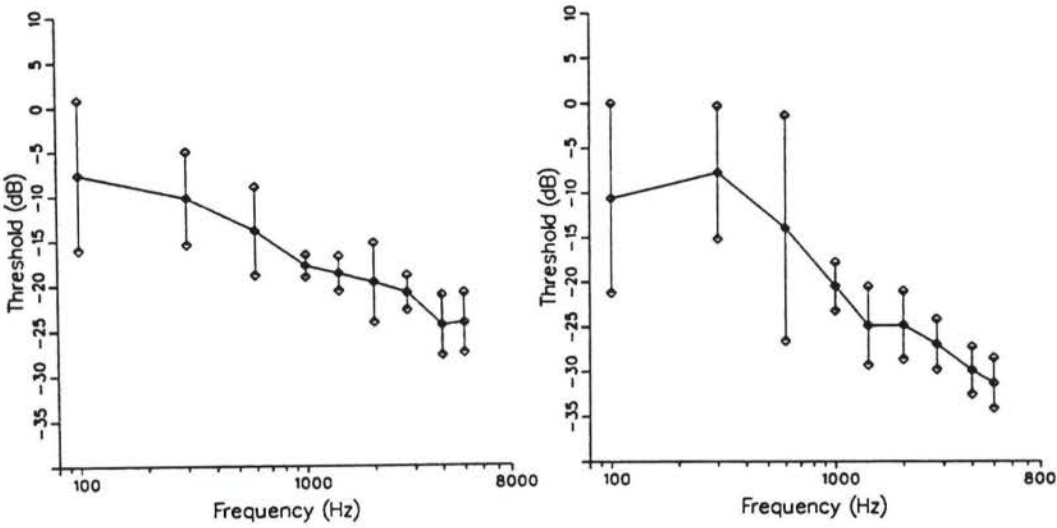


*Fig.26. 200 Hz masker at 70 dB SPL.*

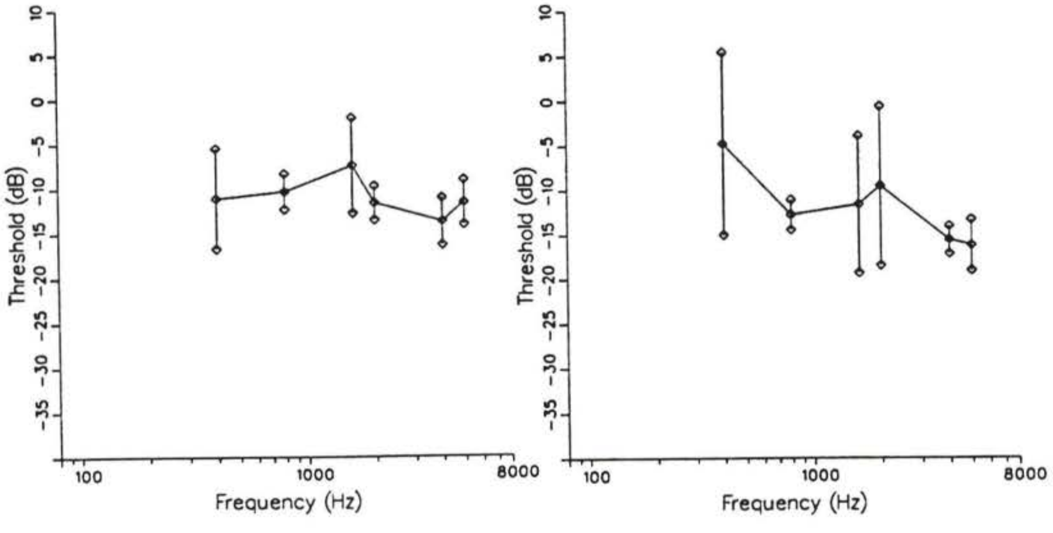


*(a)* *(b)*

*Fig.28. Average of 3 subjects, 100 Hz fundamental, 80 dB SPL, symmetric (a) and antisymmetric masker (b).*

Fundamental frequency 200 Hz

When the 200 Hz data was averaged we got the results illustrated in fig.29. Even at higher frequencies of the maskee standard deviations stay big. This illustrates the fact that most subject, the author included, found it more difficult listen to these higher pitched signals. The difference between the symmetrical and antisymmetrical case is



*(a)* *(b)*

*Fig.29. Average of 3 subjects, 200 Hz fundamental, 70 dB SPL, symmetric (a) and antisymmetric masker (b).*

not clear, although the symmetrical case has slightly higher threshold of detection, about 3 dB, the standard deviations are of the same order of magnitude. Another thing is the slope of the curves, it is only -1.5 dB/oct above 1 kHz.

### Fundamental frequency 400 Hz

At this fundamental frequency things worsen even more, subjects found it even more difficult to listen to these stimuli. Not all data was collected, but from the data collected there is no statement to be made, the standard deviations of some point almost cover the whole dynamic range over which was measured.

## CONCLUSION

The data for the 100 Hz experiment corresponded to our expectations. The experiment lines up with the theory presented earlier. Only problem was that the perception of low frequency stimuli was worse for less experienced subjects, and thus causing a big standard deviation.

For the 200 Hz experiment it is not possible to make such a clear statement. The standard deviations tend to increase as the fundamental frequency increases. It is difficult to get stable data, this maybe caused by lack of skill of the subjects.

The 400 Hz experiment showed, as far it was completed, very large standard deviations between the subjects. It is not possible to make conclusions about this data without doing further research.

ACKNOWLEDGMENTS

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