Original Article

Vibrotactile identification of signal-processed sounds from environmental events presented by a portable vibrator: A laboratory study

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Objective: To evaluate different signal-processing algorithms for tactile identification of environmental sounds in a monitoring aid for the deafblind.

Subjects: Two men and three women, sensorineurally deaf or profoundly hearing impaired with experience of vibratory experiments, age 22-36 years.

Method: A closed set of 45 representative environmental sounds were processed using two transposing (TRHA, TR1/3) and three modulating algorithms (AM, AMFM, AMMC) and presented as tactile stimuli using a portable vibrator in three experiments. The algorithms TRHA, TR1/3, AMFM and AMMC had two alternatives (with and without adaption to vibratory thresholds). In Exp. 1, the sounds were preprocessed and directly fed to the vibrator. In Exp. 2 and 3, the sounds were presented in an acoustic test room, without or with background noise (SNR=+5 dB), and processed in real time.

Results: In Exp. 1, Algorithm AMFM and AMFM(A) consistently had the lowest identification scores, and were thus excluded in Exp. 2 and 3. TRHA, AM, AMMC, and AMMC(A) showed comparable identification scores (30%-42%) and the addition of noise did not deteriorate the performance.

Conclusion: Algorithm TRHA, AM, AMMC, and AMMC(A) showed good performance in all three experiments and were robust in noise; they can therefore be used in further testing in real environments.

Keywords: Environmental sound, Identification, Narrow-band, Tactile perception, Transposing, Vibration, Vibrator

Introduction:

For humans, vision and hearing are two most important senses for monitoring the environment. Deafblind people, who have little or no use of these senses, primarily use the cutaneous senses and smell to monitor ongoing events in their environment. They rate receiving information about humans and machines in the household and traffic as most important (1). A portable monitoring aid for obtaining information about events in their surrounding has been of interest among the deafblind (1).

Several tactile aids, such as Minivib II, Tactaid II, Tactaid VII, and Sentiphone, have been developed to improve lip reading in deaf persons and to improve speech perception in profoundly hearing impaired or deaf individuals. These aids have also been helpful in monitoring of the surroundings (2-6) although they were designed for speech communication. In addition electrotactile

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stimulation has been tested for transmission of articulatory information (7).
Cochlear implantation (CI) is a more recent technique to improve speech perception. The implant sends electrical impulses that stimulate remaining functioning auditory nerve fibres in the inner ear (8, 9). The technique requires advanced surgery and functioning auditory nerves. Two cochlear implants (one in each ear) have been used successfully to obtain directional information and improve speech perception in noise (10, 11). However, the binaural implantation further increases the already high cost of CI.
Some subjects do not achieve useful speech understanding through cochlear implants, hearing aids or vibrators, but they do obtain valuable information about events in the environment although the signal processing of the aids was designed for speech reception. Our ambition has therefore been to design the signal-processing specifically for environmental sounds and not for speech, thereby hopefully achieving a better aid for those who use sign language or whose aids do not improve their speech communication.
The present study is part of a project aimed at developing a vibratory aid to improve the perception of and possibility to interpret events in the environment: a "monitoring" aid for deaf, especially deafblind persons. Monitoring means to detect, localize, and identify events in the environment. The detection and localization parts are described in a previous study (12, 13). For identification of events more information about the event is necessary. The sound (signal) produced by the events has to be processed and transformed to fit the vibratory sensitivity range of the skin. The processed signal is then presented to the deafblind subject as vibrations to a suitable skin region, e.g. fingers or thenar. The subjects are able to use the vibratory information in conjunction with contextual information and to interpret the vibrations as an event.
The vibratory sensitivity range is more limited than the hearing sense (the frequency sensitivity range of the skin is up to approx. 800 Hz, while that of hearing is 20-20000 Hz). Therefore, the sounds must be processed (4). Further, the vibratory threshold of the skin is different depending on body site, gender, temperature and several other factors (4).
In a previous study on 19 deaf participants (14), a stationary high precision wide-band vibrator (Brüel & Kjær type 4810) was used to compare eight basic algorithms and select those that are most efficient for identification of environmental sounds. In the present study, five selected algorithms will be used in three experiments with a portable vibratory aid. In previous tests, these five algorithms were regarded as good candidates for extended development. The portable vibrator with the frequency range most suitable for cutaneous stimulations (C2 Tactor) will be used to evaluate the algorithms with respect to identification of environmental sounds.
The experiment was conducted in three stages: Exp.1, 2, and 3. In Exp. 1, the environmental sounds were signal processed off line (pre-processed) using the five algorithms, recorded and presented to the subjects as vibrations.
In Exp. 2 and 3, the tests were performed in a sound-treated room and signal processing of the sounds was conducted in real time. In both tests, the original sounds played via loudspeaker were picked up by a microphone (AKG C 417) mounted in a headband, signal-processed using the algorithm(s) chosen in Exp. 1, and presented as vibrations to the thenar eminence and fingers of their dominant hand. To test the robustness of the algorithms, a white noise was used to partly mask the environmental sounds. A signal-to-noise ratio (SNR) of +5 dB was chosen, which is below the limit (SNR = + 8 dB) for the direction indication algorithm (12).
The experiments were repeated twice (test and retest), and the identification results were only evaluated in the second presentation (retest).

Purpose

The purpose is to use a portable vibrator to:
1)Evaluate different algorithms and choose the algorithm(s) most suitable for vibrotactile identification of sounds from environmental events

(preprocessed).
2)Test the chosen algorithm(s) with acoustic stimuli, processed in real time without background noise.
3)Test the chosen algorithm(s) with acoustic stimuli, processed in real time with background noise.

Material and methods

Five volunteers (S1-S5), sensorineurally deaf subjects (3 females and 2 males) between 22-36 years of age, participated in the tests (see Table I). Three of the subjects had hearing aids and one had a cochlear implant (the subjects were not aided during the tests). The subjects had participated in a previous study (14) and were familiar with the general test methodology. They had not received feedback and the identity of the sounds was unknown to them. Only five out of the 19 subjects in the previous study (14) were able or willing to continue their participation, primarily because each experiment took at least six hours (approx. 20 hours/subject in total). New subjects were not included because they would not have had the same baseline experience (training in (14)). Therefore, the number of subjects was limited to five.

The test sounds/events used in the present experiments were the same 45 environmental sounds (see Table II) used in previous experiments. The 45 environmental sounds/events were selected by normal hearing and deafblind persons, who classified the events as most important to be informed about (1).

In Exp. 2 and 3, Sound 3, dripping water, was tested but excluded from the calculation of the identification scores because the sound was found to be distorted.

Equipment

Exp. 1 (preprocessed, directly fed signals)

The algorithms were implemented in Matlab 7.0.4. The sounds were played by a computer (Pentium® 4 CPU 1.70 GHz, 256 MB RAM) and presented using a portable vibrator (C2 Tactor). The vibrator had the widest bandwidth of all the portable vibrators in the market (at the time of the tests), but still a smaller bandwidth than the vibrator (Brüel & Kjær type 4810) used in the previous study (14) and the sensitivity range of the skin (4).

The vibrator was supplied with an equalizing filter to remove a peak at approx. 200 Hz and to make the frequency response of the vibrator broader. The resulting frequency response was flat up to 80 Hz, with a dip of approx. -20 dB around 200 Hz, a peak of approx. 10 dB around 500 Hz, and a roll off of 40 dB/octave above 500 Hz. The resulting frequency response was similar to the frequency response for sensitivity thresholds of the skin for frequencies below 500 Hz. The equalizer thus resulted in a wider vibrator frequency response, but also a partial adaptation, i.e. attenuating in the best sensitivity range of the skin, the frequencies below 500 Hz, to the vibratory thresholds of the skin (14, 15).

Exp. 2 and 3 (real time processing, acoustic presentation)

The sounds were presented through a loudspeaker (Bose 101 Music Monitor) in a sound-treated room, picked up by a microphone (AKG C 417), processed in a signal-processing program (Aladdin Interactive DSP 3.0) in real time and sent to the vibrator. The environmental sounds were presented at 70 dBA and a white noise at 65 dBA was used as background (masking) noise (SNR=+5 dB) in Exp. 3. The SNR in the present study was set lower than the SNR (+8 dB) used in the previous study (12), where the direction perception algorithm worked best when the SNR was higher than +8 dB.

The vibrator was supplied with an equalizing filter with a transfer function more flat than the equalizing filter used in Exp. 1. The resulting frequency response had a ripple of 3 dB between 80-300 Hz and a slope of approx. 24 dB/octave above about 300 Hz.

Signal-processing algorithms

The 45 environmental sounds were processed using two frequency transposing (TRHA and TR1/3) and three modulating (AM, AMFM and

AMMC) algorithms (see Table III and description below, for further details see (16)). These algorithms had shown good results in previous vibrotactile identification experiments with a wide-band stationary vibrator and were chosen as good candidates for further testing (14). The basic alternative with the equalizing filter is called Alt 1 (see Figure 1).

The sounds processed with Alt 1 were also adapted to the vibratory threshold of the skin with the same adaptation algorithm (Algorithm EQ) as used in (14). The adapted alternative of algorithms is called Alt 2 (adapted algorithms, Algorithm(A)).

In Exp. 1, the 45 environmental sounds were processed using five different algorithms. There were two alternatives (Alt 1 and Alt 2) for Algorithms TRHA, TR1/3, AMFM and AMMC. Algorithm AM was not tested in Alt 2, because the output is dominated by one frequency, which would not be changed after adaptation. In total, nine algorithms (TRHA, TRHA(A), TR1/3, TR1/3(A), AM, AMFM, AMFM(A), AMMC, and AMMC(A)) were evaluated.

In Exp. 2 and 3, Algorithm TRHA, TR1/3 and AMMC were modified (see below) and Algorithm AMFM and AMFM(A) were excluded. In these experiments, owing to lower computer capacity, only Algorithm AMMC had two alternatives (AMMC and AMMC(A)), with and without adaptation to the vibratory thresholds of the skin (thus a total of five algorithms were tested, see Table III).

All algorithms, irrespective of earlier adaption (both in Alt 1 and Alt 2), were equalized (partially adapted to the sensitivity thresholds of the skin in the frequency range below 500 Hz as describe in section Equipment, Exp. 1) using the equalizing filter for the vibrator. For example, using Algorithm AMMC(A), first the input signal was processed according to the description of the algorithm then adapted to the skin using the adaptation algorithm (EQ) and finally processed using the equalizer to the vibrator described in section Equipment, Exp. 1, or the equalizer used in Exp. 2 and 3 (partially adapted).

Algorithm TRHA

In Exp. 1, the 16 frequency components with highest amplitude in the range 100–8000 Hz were transposed to the frequency range 30–480 Hz using Df=30 Hz. The order of the frequency components was kept the same as in the original sound. In Exp. 2 and 3, the eight frequency components with the highest amplitude in the range 100–4000 Hz were transposed to the range 187–437 Hz using Df»31 Hz.

Algorithm TR1/3

In Exp. 1, the frequency components within the range 150-300 Hz were transposed to the frequency range 50-200 Hz. Further, the input signal was fed to a filter bank (Butterworth band-pass filters of order 3) consisting of 13 pass bands (300-400, 400-500, 500-600, 600-800, 800-1000, 1000-1200, 1200-1600, 1600-2000, 2000-2400, 2400-3200, 3200-4000, 4000-5300, and 5300-6600 Hz). The outputs from the filters were rectified and low-pass filtered (3rd order Butterworth, cut-off frequency 10 Hz), thus obtaining an envelope signal for each pass band. These 13 signals were then used to amplitude modulate 13 carrier waves, with frequencies 307, 353, 379, 419, 431, 461, 509, 557, 577, 593, 631, 673, and 701 Hz, respectively. Furthermore, the carriers were frequency modulated by a random noise dither signal, to avoid pronounced low frequency interference patterns. The total output was obtained by adding the transposed signal (50-200 Hz) and the 13 modulated signals described above. This algorithm can also be classified as being of band-spread type.

Algorithm TR1/3 was modified in Exp. 2 and 3 due to lower computer capacity. The number of filter banks (Butterworth band-pass filters of order 3) was decreased to six, consisting of the six pass bands (300-500, 500-800, 800-1200, 1200-1800, 1800-2700 and 2700-3900 Hz). The six carrier waves were also changed to frequencies 206, 338, 440, 570, 740, and 960 Hz, respectively. The relative frequency difference between carrier signals was almost 30% ($Df/f \approx 30\%$).

Algorithm AM

A 250 Hz sine signal was amplitude modulated by the envelope of the input signal. To extract the envelope of the input signal, the signal was first rectified and then low-pass filtered using Butterworth low-pass filter of order 3 at a cut-off frequency of 10 Hz.

Algorithm AMFM

A 250 Hz sine signal was both amplitude modulated (by the envelope of the input signal extracted by low-pass filtering at 10 Hz as in AM) and frequency modulated (by the derivative of the low-pass filtered input signal envelope, deviation ± 20% of the carrier frequency). The modulated carrier frequency varied between 200 and 300 Hz. This algorithm and the adapted alternative, AMFM(A), were not used in Exp. 2 and 3 because it had the poorest identification result in the Exp. 1.

Algorithm AMMC

The input signal was band-pass filtered (Butterworth filter of order 3) in six bands (120–240, 240–480, 480–960, 960–1920, 1920–3840 and 3840–6000 Hz, respectively). Thereafter, the envelope (extracted by rectifying and low-pass filtering at 10 Hz) of the output signal from each filter was used to amplitude modulate sine signals with the frequency 53, 79, 113, 197, 317 and 479 Hz, respectively in Exp. 1.

In Exp. 2 and 3 the corresponding carrier frequencies were 55, 105, 215, 335, 445 and 650 Hz, respectively.

Adaptation to the vibratory threshold (Alt 2)

In Alt 2, the output signal from the algorithm Alt 1 was further adapted to the vibratory threshold of the skin using a transfer function (Algorithm EQ, Equalizer, in the previous study (14)) representing the vibratory threshold of the skin (compensating for sensitivity differences by attenuating mid-frequencies and amplifying low and high frequencies), according to Verillo (15) and Ranjbar et al. (14). The partially adapted (Alt 1) and adapted (Alt 2) alternatives of the algorithms were tested separately.

In Exp. 1, Algorithm TRHA, TR1/3, AMFM, and AMMC had two alternatives (adapted and unadapted) labelled TRHA(A), TR1/3(A), AMFM(A), and AMMC(A), respectively.

In Exp. 2 and 3, Algorithm AMMC was the only algorithm tested after adaptation to the vibratory thresholds of the skin (the limitations of the real time processing capacity prohibited adaptation of Algorithm TRHA and TR1/3).

Procedure

Exp. 1 (preprocessed, directly fed signals)

The subjects were seated in a quiet room and held the vibrator on the thenar eminence of their dominant hand, thereby also keeping the fingers in contact with the vibrator surface. The algorithms were presented in random order for each subject. The subjects did not receive any feedback about the correctness of their responses. After the subjects had tested all (nine) algorithms with the 45 events in random order (test), the presentation was repeated (retest) in same way (new random order) for each subject.

Exp. 2 and 3 (real time processing, acoustic presentation)

The subjects were seated in the centre of a sound-treated room surrounded by 12 loudspeakers placed in a circle, numbered from 1 to 12, with number 12 in front of the subject and continuing clockwise (17). The radius of the circle was 140 cm.

The subjects wore a headband on which the microphone was mounted and held the vibrator on the thenar eminence of their dominant hand. The sounds presented from the loudspeaker and picked up by the microphone were sent to the computer to be processed in real time using one of the five algorithms (TRHA, TR1/3, AM, AMMC and AMMC adapted) that had resulted in the highest identification scores in Exp. 1. Finally, the processed signal was sent to the vibrator.

In Exp. 2, the original sounds were presented via Loudspeaker 12 (0 azimuth) at 70 dBA.

In Exp. 3, the original sounds were presented via Loudspeaker 2 (+60 azimuth) at 70 dBA, and

a white noise at 65 dBA was played via Loudspeaker 10 (-60 azimuth).
In all three experiments, the subjects were allowed to adjust the amplitude of the vibrations within certain limits and to take the time they needed to identify the environmental sounds.
For each algorithm, the subjects had access to a list of sounds (events) consisting of 45 items.
The subjects sensed the vibrations presented and indicated the corresponding sound (one of the 45 sounds). The sounds were presented up to five times if the subject required repetitions. The algorithms were tested in a different random order for each subject. No feedback was given. An experiment could be divided into parts running over two or three days. Breaks were taken when required by the subject. The tests took approximately 20 hours for each subject. Each experiment was repeated in the same way (new random order) for each subject directly after they had tested all algorithms (totally nine algorithms in Exp. 1 and five algorithms in Exp. 2 and 3) in each experiment.

Assessment

A correct response resulted in 1 point and an incorrect response resulted in 0 points. Thus, in Exp. 1, the maximal identification score was 45 for the total of 45 events, while in Exp. 2 and 3, the maximal identification score was 44 for the total of 44 events (Sound 3, dripping water, was excluded because it was distorted). In all three experiments, the algorithms were tested twice (test and retest). Only the results in the second session, retest, were evaluated.

A descriptive non-parametric statistical analysis was performed.

Results:

The results of vibratory identification of 45 environmental sounds processed by different algorithms (nine algorithms in Exp. 1 and five algorithms in Exp. 2 and 3) and identified by the five subjects were determined by summing up the points (see assessment section) and creating identification scores for each participant and each algorithm.
The results of Exp. 1, Exp. 2 and Exp. 3 will be presented separately.

Exp. 1 (preprocessed, directly fed signals)
The percentage identification score at retest is shown in Figure 2 for each subject and each of the five algorithms.
As indicated in Figure 2, the median identification score for the algorithms varied between 27% and 47% (median =40%), where Algorithm AMFM had the lowest median value and Algorithm TRHA(A) the highest (see also Table IV).
The subjects' median identification score across algorithms varied between 27% and 47% (median =40%, see Figure 2, Median/subj). Subject 1 (S1) obtained the highest identification scores when testing Algorithm TRHA(A), S2 and S3 when testing AMMC(A), S4 when testing TRHA(A), and S5 when testing TRHA and AMMC(A).

Adaptation to the skin sensitivity (Alt 2)
Algorithm TRHA, TR1/3, AMFM and AMMC were also tested after adaptation to the vibratory sensitivity features of the skin (Alt 2, compensating for sensitivity differences by attenuating mid-frequencies and amplifying low and high frequencies). Algorithm TRHA and AMFM had better, Algorithm TR1/3 had poorer and AMMC had similar identification scores when they were adapted to the skin, but the differences were small (see Figure 2, and Table IV).

Exp. 2: (real time processing, acoustic presentation)
The percentage identification scores for environmental sounds signal-processed in real time are shown in Figure 3 for each subject and algorithm.
As seen in Figure 3, the median scores for the five algorithms varied between 23% and 41% (median =36%), where Algorithm TR1/3 had the lowest and Algorithm AMMC(A) had the highest median value (see also Table IV).
The subjects' median identification score across

algorithms varied between 23% and 50% (median =36%, see Figure 3, Median/subj). S1 obtained the highest identification score when testing Algorithm TRHA, S2, S3, and S4 when testing AM, and S5 when testing AMMC(A).

Adaptation to skin sensitivity (Alt 2)

All subjects had higher identification scores when testing Algorithm AMMC(A) than Algorithm AMMC, except S1 who had equal identification scores in both.

Exp. 3 (real time processing, acoustic presentation in background noise)

The subjects tested the same algorithms as in Exp. 2, but with a 65 dBA white noise added as background (masking) noise, SNR=+5 dB.

The identification scores for the tests are shown in Figure 4 for each subject and algorithm. As seen in Figure 4, the median values varied between 27% and 41% (median= 36%) for the five algorithms. Algorithm TR1/3 had the lowest and Algorithm AMMC(A) the highest and median value (see Table IV).

The subjects' median identification score across algorithms varied between 27% and 43% (median =32%, see Figure 4, Median/subj). S1 obtained the highest identification score when testing Algorithm TRHA, S2 when testing Algorithms TRHA and AMMC, and S3, S4, and S5 when testing AMMC(A).

Adaptation to skin sensitivity (Alt 2)

All subjects (except S2) had higher identification scores for Algorithm AMMC(A) than for Algorithm AMMC.

The identification scores for the algorithms were also compared between Exp. 1, Exp. 2 and Exp. 3. All Algorithms had better identification scores in Exp. 1 than in Exp. 2 or Exp. 3, except Algorithm AMMC(A), which had a one percentage unit lower median value in Exp. 1 (40%) than in Exp. 2 and 3 (41%).

In Exp. 3, where noise was added (SNR=+5 dB), Algorithm TR1/3 and AMMC had better identification scores than in Exp. 2, while TRHA, AM, and AMMC(A) had equal identification scores in both experiments. Thus noise at +5dB did not deteriorate identification scores. Note that the ranking order of the algorithms was the same in Exp. 2 and 3 (see Table IV).

In summary, Algorithm TRHA, AM, AMMC, and AMMC(A) had the highest median identification score values in all three experiments. Algorithm AMFM, in Exp. 1, and Algorithm TR1/3, in Exp. 2 and 3, had the lowest median value.

Algorithm TRHA and AMMC had better and Algorithm TR1/3 and AMFM had poorer identification scores when they were adapted to the skin, but the differences were small. Addition of noise at +5 dB SNR in Exp. 3 did not deteriorate the identification scores.

Discussion

The goal of the investigation was, first, to compare the algorithms and identify those that are suitable for vibratory identification of sounds from environmental events and, second, to test the chosen algorithm(s) in an acoustic environment with processing in real time without (Exp. 2) and with (Exp. 3) added masking noise. Below, first some aspects of the methods and then the results will be discussed.

Methodological aspects

Subjects

The subjects participated in all three tests. They had also tested the algorithms in previous studies (14) and were experienced with the test material, but had never received feedback on the identity of the test sounds. They were deaf (the subjects using a hearing aid or cochlear implant were not aided during the tests) and could not hear the sounds produced by the vibrator. Therefore, we did not need to mask their hearing and avoided thereby the possible problems associated with incomplete masking. Using deaf instead of deafblind subjects (for whom the portable vibratory aid is intended) decreased the possible communication and logistic problems. Interpreters are not always available, and tests would have taken more time, causing subjects to become tired and thus decreasing their focus and concentration. On the other hand, using deafblind subjects would probability have led to better identification scores, because deafblind subjects are more used to interpreting vibrations than are sighted individuals (18). Future field tests will be performed with deafblind persons.

The small number of subjects makes statistical analysis difficult. Only five of the 19 subjects in the study (14) were able and willing to continue this step of the development for various reasons (the tests time was approx. 20 h). New subjects would not have fulfilled the baseline condition (they would not have had experience from the previous study (14)). Even though all five participants had taken part in the previous study (14), they also had different levels of earlier general experience and use of vibrations. Subjects S1, S4, and S5 were born deaf and were used to hearing aids, and the vibrations produced by the low frequency components of the environmental sounds. They regularly had high identification scores. S2 (who did not use any hearing aid) and S3 (who had used a cochlear implant for three years and was deaf at age 24) had low identification scores probably because they were not used to interpreting vibrations.

Equipment

The vibrator is lightweight, portable and suitable for use in field tests. An equalizing filter is employed to obtain broader frequency response of the vibrator in the frequency range of interest. For Algorithm TRHA, TR1/3, AMFM and AMMC, equalization has the potential of improving the identification performance.

The available computer system, used in Exp. 2 and 3, set limitations for data size and execution speed. This forced us to reduce the number of transposed frequencies in Algorithm TRHA and TR1/3, and to omit the filter for full adaptation (Alt 2) to the vibratory threshold of the skin. A more powerful computer system will be used in further tests to overcome these limitations.

Aspects of Results

The primary novelties of the present study are the use of a portable vibrator with a more limited bandwidth than the stationary vibrator and the acoustic presentation of environmental sounds in a test room and processed in real time without and with background noise.

From the outset, there were eight different algorithms, which have been tested in one auditory (16) and four different vibrotactile tests (six of them have also been tested after adaptation to the vibrotactile threshold curve). Algorithm TRHA, AM, AMMC and AMMC(A) had high identification scores, covered the entire spectrum of the original sounds and could be implemented in a vibrotactile aid using our available technology. The algorithms that had the most pronounced shortcomings and poor identification results had already been discarded.

The Algorithms are ranked after median identification score value in Table IV. Note that the rank order was the same in the two acoustic experiments (Exp. 2 and 3). The median value of Algorithm TRHA tended to be higher in Exp. 1 (40%) than in Exp. 2 and 3 (36%), which may partly depend on the number of frequencies, which was decreased from 16 to eight (eight frequencies represent the original sound). No existing aid could be found that uses an algorithm similar to TRHA, and it seems to be a good candidate for implementation.

Algorithm TR1/3 was one of the algorithms that had high identification scores in the previous study (14) and in Exp. 1, but the poorest results in Exp. 2 and 3. The differences between the identification results for the algorithm in the previous study and the pooled results of the current study can be explained by the fact that the bandwidth of the portable vibrator was considerably smaller than that of the stationary vibrator used in the previous study. The lower scores in Exp. 2 and 3 compared to Exp. 1 can partly be explained by the effect of the change in carrier frequencies to 260, 338, 440, 570, 740 and 960. The choice of frequencies was based on the fact that the skin has a frequency discrimination of 30%. However, the frequencies above 400 Hz were attenuated using the equalizing filter to the vibrator. Furthermore, at higher frequencies such as 740 and 960, the skin does not have good sensitivity and selectivity (4). The low sensitivity combined with the band-limited output from the vibrator makes the high frequency components difficult to sense.

Algorithm AM had high identification score in all three tests. The algorithm also had high identification results in a previous study (14) (see Table IV). The high score of the algorithm is compatible with the poor frequency discrimination and resolution of the skin. Algorithm AM is similar to the tactile aid MiniVib II (3), the difference being that Algorithm AM uses the whole spectrum of the environmental sound, whereas MiniVib II covers the frequency range 500-2300 Hz (it is designed for speech perception). Algorithm AM can be loaded into a tactile aid using a vibrator with a fixed frequency, 250 Hz.

Frequency modulation of carrier frequencies by noise in addition to attenuation of frequencies around 250 Hz seems to have had a negative effect on identification results. Algorithm AMFM and AMFM(A) had the highest results in the previous study (14), but the lowest in the present study (see Table IV), which can partly be explained by the use of the equalizer on the narrow-band vibrator, which attenuated frequencies below 500 Hz (specially around 250 Hz).

Algorithm AMMC had poorer results than did Algorithm TRHA in Exp. 1. In Exp. 2 and 3, it had the same results as the other algorithms. This algorithm had better results in all three tests after adaptation to the vibratory thresholds of the skin. Algorithm AMMC is similar to the signal-processing method used in Tactaid VII, where the outputs from seven different filter bands in Tactaid VII are sent to seven different vibrators, which can be placed on different body sites (4, 19). Tactaid VII was evaluated in a study by Reed and Delhorn (2) using profoundly deaf subjects and environmental sounds in four different environments (general home, kitchen, office and outdoors). The subjects' average identification scores over all four settings was 65% and the subjects had received training consisting of 600 trials with correct-answer feedback in each of the four environments and had access to a sound list containing the 10 sounds. The corresponding average identification score in the present study in Exp. 3 was 36% (using Algorithm TRHA), 25% (TR1/3), 36% (AMMC) and 40% (AMMC(A)). The present results are promising, because in our study the subjects were less experienced (they did not receive any feedback) than were subjects in the study by Reed and Delhorn (2). The participants in the present study chose the answers from a list 45 sounds, where the guessing chance is lower than when the number of sounds is 10. One of the advantages of the tactile aid in present study is the use of only one vibrator (7 vibrators in Tactaid VII), which decreases the requirement of a power supply and is easier to fit to the body. The physical design of aids is one of the most important features for the individual's choice of aid (4).

Performance in noise

The used level of SNR (+5 dB) has obviously not affected the results negatively, as the algorithms had equal or higher (AMMC and TR1/3) identification scores than in Exp. 2. In Algorithm TRHA, the maximum magnitude frequency components are used, and adding white noise did not change the relationship between the magnitudes. In Algorithm TR1/3, AM, AMMC, and AMMC(A), the envelope is extracted by low-pass filtering at a cut-off frequency of 10 Hz, thereby filtering out the noise.

In further studies, the signal-processing algorithms will be combined with the directional perception algorithm developed in the previous studies (12, 13), which works best when SNR is higher than +8. The good results in Exp. 3 show that the algorithms even work better than the directional perception algorithm in noise.

Selection of algorithms for further application

As described above, Algorithm TRHA, AM, AMMC and AMMC(A) gave about equally good results and are thus equally good candidates for implementation in a portable vibratory aid. They had high identification scores in tests with and without background noise and were easy to implement. Algorithm TR1/3, used in Exp. 1, is also a good candidate, but requires more advanced computer and signal-processing technology. It is difficult to choose only one algorithm to test in the field, because the difference between the median values for Algorithm TRHA, AM, AMMC and AMMC(A) was small. One possible solution could be to choose the algorithm for which the subject had the best identification scores in Exp. 3 (noise added), particularly because there are great differences in identification results between subjects. It would therefore seem reasonable to consider a personalized version of the system, where every person can use the algorithm of his/her choice.

Summary and Conclusion

Five signal-processing algorithms (TRHA, TR1/3, AM, AMFM, AMMC), of which four had two alternatives (with and without adaption to vibratory thresholds, in total nine algorithms), were evaluated for tactile identification of environmental sounds in a monitoring aid for the deafblind. Five sensorineurally deaf or profoundly hearing impaired subjects identified 45 environmental sounds processed by the algorithms in three experiments. In Exp. 1, where the sounds were preprocessed and directly presented, the identification scores varied between 27% and 47%. Algorithm AMFM and its adapted alternative (AMFM(A)) consistently had the lowest scores and were thereby excluded in Exp. 2 and 3. The adapted alternatives of Algorithm TRHA and TR1/3 were also excluded in Exp. 2 and 3 due to technical limitations.
In Exp. 2 and 3, the sounds were presented in an acoustic test room, without or with background noise (SNR=+5 dB), and processed in real time. The identification scores in Exp. 2 varied between 23% and 41%, and in Exp. 3 the scores varied between 27% and 41%. The algorithms ranking order based on median value were the same in both experiments indicating good test reliability. Addition of the noise did not deteriorate the performance. Algorithm TRHA, AM, AMMC, and AMMC(A) showed good results in all three experiments and were selected to further testing in real environments.

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Table I: Description of subjects (F=Female, M=Male, CI= Cochlear Implant)

Subject	Age	Sex	Hearing Loss (age)	Hearing aid/CI
S1	33	M	Birth	Hearing aid
S2	22	F	Birth	No hearing aid or CI
S3	36	F	24	CI
S4	26	M	Birth	Hearing aid
S5	26	F	Birth	Hearing aid

Table II: Sound number and the label of the environmental event (sound) used in the experiments.

Sound no.	Environmental sound	Sound no.	Environmental sound	Sound no.	Environmental sound
1	Doorbell	16	Two men talking	31	Noise from breeze
2	Stream murmur	17	Telephone signalling several times	32	Spectator excitement
3	Dripping water	18	Door opening and closing	33	House alarm
4	Heavy traffic	19	Frying bacon	34	Copier
5	Car signalling a few times	20	Water running	35	Restaurant buzz
6	Barking dog	21	Coffee maker	36	Keyboard
7	Wave	22	Washing machine washing	37	Cutting wood
8	People laughing	23	Vacuum cleaner	38	Cat meowing
9	Bird song	24	Toilet washing twice	39	Signal at crossing
10	Thunder followed by rain	25	Rain on window	40	Hammer-blow
11	Train which slows down and drives past	26	Boiling water	41	Opening champagne twice
12	A person sneezing	27	Tractor comes, stops and idling	42	Riding horse
13	Motorcycle passing	28	Loudspeaker announcement	43	Hiccup
14	Bicycle bell	29	Someone walking on gravel	44	Cow mooing
15	Signal from ice cream car	30	Cutlery clatter	45	Helicopter

Table III: The algorithms used to process the sounds in the experiments. There were two alternatives (versions) of the algorithms TRHA, TR1/3, AMFM and AMMC; in the second alternative, the sounds were also adapted to the vibratory thresholds of the skin.

Algorithm	Description
TRHA	TRansposing the frequency components with Highest Amplitude in the range 100–8000 Hz to the range 30–480 Hz (two alternatives in Exp. 1)
TR1/3	TRansferring the sum of the complex frequency components within every 1/3 octave within the range 150–6600 Hz to the range 50–701 Hz (two alternatives in Exp. 1)
AM	Amplitude Modulation of a 250 Hz carrier wave
AMFM	AMplitude and Frequency Modulation of a 250 Hz wave (two alternatives in Exp. 1)
AMMC	Amplitude Modulation with Multiple Channel (two alternatives in Exp. 1, 2 and 3)

Table IV : Ranking order of Algorithms after median value of identification scores in previous study (14), Exp. 1, Exp. 2, and Exp. 3. The figures were in parentheses represent the median value of algorithms in each experiment.

Rank order	Study (14)	Exp. 1	Exp. 2	Exp. 3
1	AMFM	TRHA(A) (47%)	AMMC(A) (41%)	AMMC(A) (41%)
2	TRHA	AM (42%)	AM (39%)	AM (39%)
3	AMMC(A)	TRHA, TR1/3, AMMC, AMMC(A) (40%)	TRHA (36%)	TRHA (36%)
4	AMMC	TR1/3(A) (38%)	AMMC (30%)	AMMC (34%)
5	AM	AMFM(A) (29%)	TR1/3 (23%)	TR1/3 (27%)
6	TR1/3	AMFM (27%)		
7	TRHA(A)			
8	TR1/3(A)			
9	AMFM(A)			

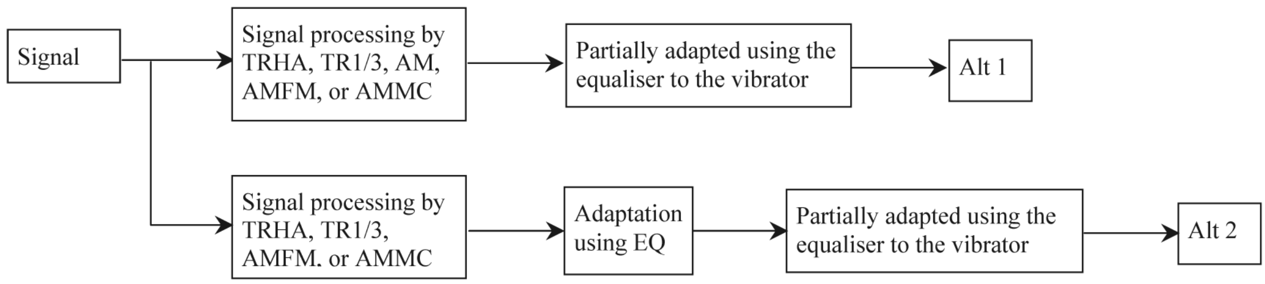

Figure 1: *Illustration of the different signal processing steps in partially adapted (Alt 1) and adapted (Alt 2) alternatives of the algorithms.*

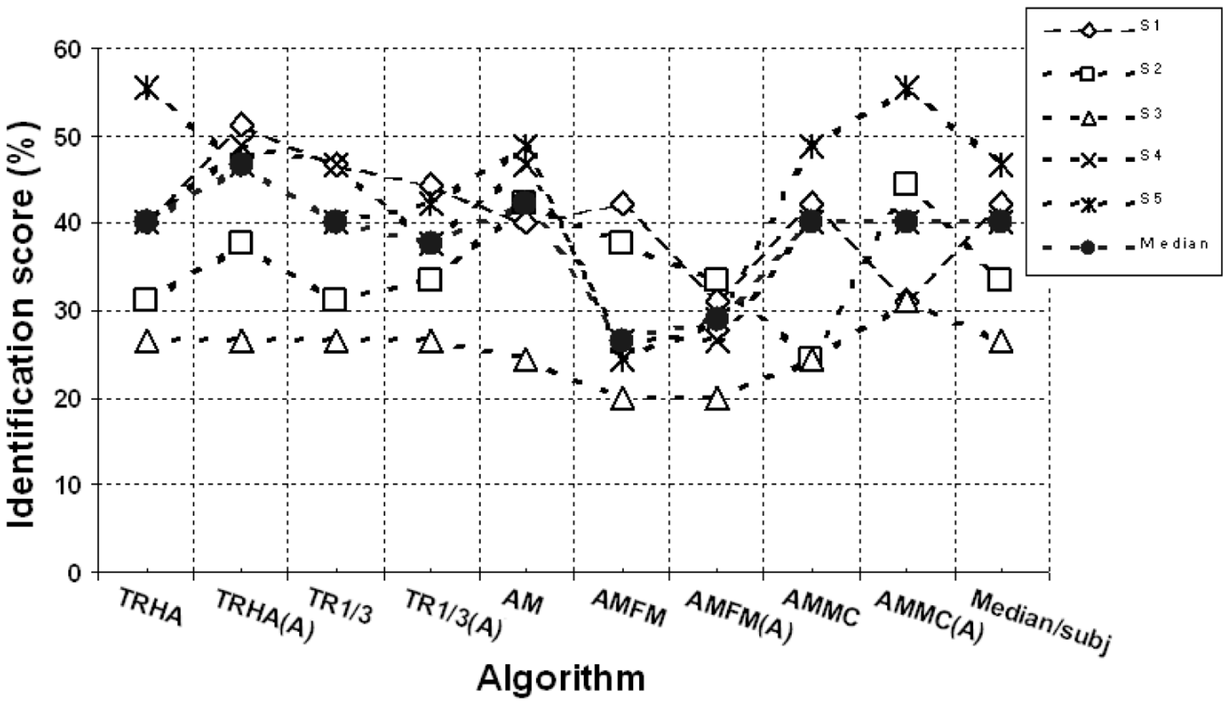

Figure 2*: The individual identification scores and percentage median values of vibratory identification of environmental sounds processed by five different algorithms and tested by five subjects*

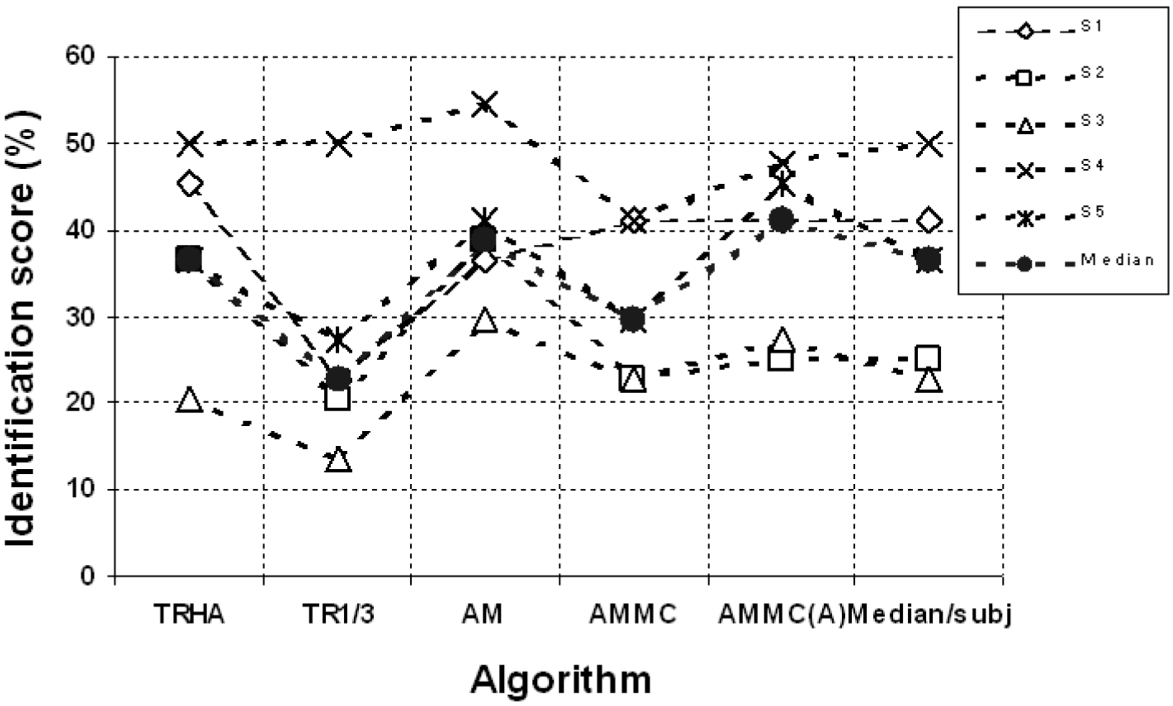

Figure 3: *The individual identification scores and percentage median values of vibratory identification of environmental sounds processed by different algorithms and tested by five subjects. The sounds were signal processed and presented in real time in a sound-treated room without masking noise.*

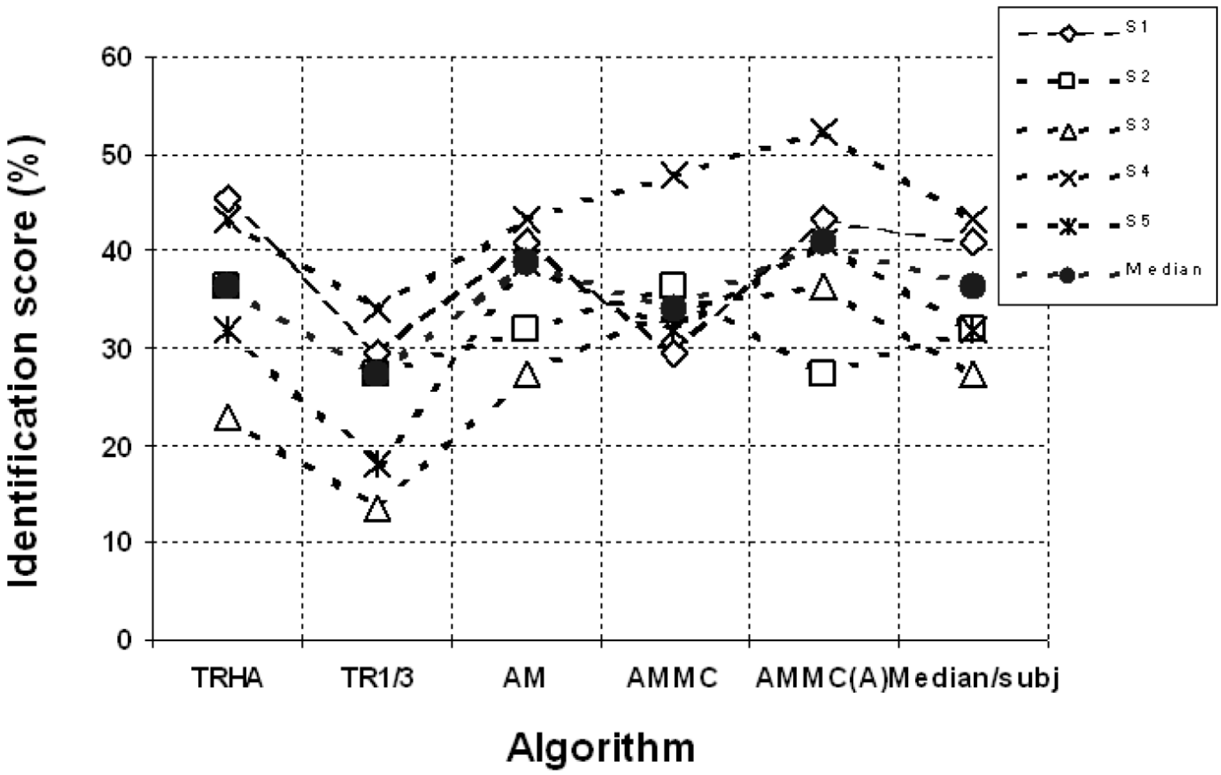

Figure 4: *The individual identification scores and percentage median values of vibratory identification of environmental sounds processed by different algorithms and tested by five subjects. The sounds were signal processed and presented in a sound-treated room with broadband masking noise at SNR=+5 dB.*

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