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Case Report / series

Vibrotactile detection,identification and directional perception of signal-processed sounds from environmental events: A pilot field evaluation in five cases

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Objective: Conducting field tests of a vibrotactile aid for deaf/deafblind persons for detection, identification and directional perception of environmental sounds.

Subjects & method: Five deaf (3F/2M, 22–36 years) individuals tested the aid separately in a home environment (kitchen) and in a traffic environment. Their eyes were blindfolded and they wore a headband and holding a vibrator for sound identification. In the headband, three microphones were mounted and two vibrators for signalling direction of the sound source. The sounds originated from events typical for the home environment and traffic. The subjects were inexperienced (events unknown) and experienced (events known). They identified the events in a home and traffic environment, but perceived sound source direction only in traffic.

Results: The detection scores were higher than 98% both in the home and in the traffic environment. In the home environment, identification scores varied between 25%-58% when the subjects were inexperienced and between 33%-83% when they were experienced.
In traffic, identification scores varied between 20%-40% when the subjects were inexperienced and between 22%-56% when they were experienced. The directional perception scores varied between 30%-60% when inexperienced and between 61%-83% when experienced.

Conclusion: The vibratory aid consistently improved all participants' detection, identification and directional perception ability.

Key words: Deaf, Deafblind, Directional perception, Environmental sound, Tactile perception

Introduction:

Deafblind people have three different functional areas that are severely impaired: mobility (ability to move around in an environment and physically orient oneself), communication (exchange of information) and monitoring of surrounding activities. In the present context, monitoring refers to the detection, identification and directional perception of an event (1).

Monitoring the environment is a problem that deafblind people consider important. Some have residual hearing and may benefit from hearing aids, for instance aids with transposing algorithms. Others may have cochlear implants, CI, (2-4). For those who have severely impaired hearing and vision, other senses are especially important. Vibrations produced by events, odours, and draughts are used to detect and identify environmental events (5). Even deaf people with adequate visual functioning have problems with monitoring and can benefit from technical aids (6).

A portable vibratory aid for monitoring events in the environment could help the deafblind to better comprehend the world around them, thus increasing their feeling of security and improving their control over their surroundings. The restricted frequency range and poor selectivity of the skin, however, limit tactile detection and particularly identification of events, especially those emitting high frequency sounds. Thus, sounds must be processed and adapted to the properties of the vibratory sense (7,8).

Sentiphone, MiniVib II and Tactaid VII are three examples of tactile aids designed for speech perception for profoundly hearing impaired persons who receive insignificant or no benefit from conventional hearing aids for perceiving speech (7,9,10). The aids are also used to improve the hearing impaired person's speech reading, and as a side effect they also improve perception of environmental sounds (11). In a study by Traunmüller, when subjects used Sentiphone as a speech reading aid, their average fault rate decreased from 24%, when they used only visual information, speech reading, to 3.3%, when they combined the visual information and the tactile information from the Sentiphone (10,12). Regarding perception of environmental sounds, the deaf subjects' subjective rating of their handicap, on a scale from 0% (no handicap) to 100% (total handicap), was 36.6% when they were aided by MiniVib II compared to 60.5% when they were unaided (7).

Reed and Delhorne (11) evaluated the ability of experienced deaf users of the vibrotactile aid, Tactaid VII, to identify environmental sounds. The test-sounds were four different closed sets of 10 sounds each, representing different environmental situations (Home, Kitchen, Office and Outdoors). The results showed that after training the subjects could identify almost 60% correctly on each of the four sets in a laboratory study.

In addition, electrotactile stimulation has been tested for transmission of articulatory information (13), but so far not used for environmental information.

Tactile aids are an alternative to CI in postlingually deaf persons who can obtain improved environmental perception, but not successful oral speech communication through cochlear implantation. Such individuals can also avoid the surgery required for cochlear implantation and thereby its negative side effects, such as infections (14-18).

The general purpose of the present study is to develop a vibrotactile aid for monitoring of the environment, i.e. a device designed for environmental sounds, but not for speech. A laboratory prototype of a three-microphone system for real-time directional analysis of sound sources has been developed within the research team. This first prototype (1,19,20) was mounted on eyeglasses. Sound source direction was determined by a cross-correlation algorithm (calculation method), and eight directions were coded to two vibrators placed behind the ears, signalling eight directions.

Identification of the events has been studied in normal hearing (21) and deaf subjects (22,23). These subjects have been tested with environmental sounds processed with selected algorithms in order to determine which algorithm(s) gives the best condition for vibrotactile event identification.

In the first study, 45 representative environmental sounds were signal processed using eight different algorithms (22). Three transposing algorithms, three modulating algorithms, one filtering algorithm and the unprocessed signal were tested. The processed sounds were identified by 19 deaf subjects using a stationary wide-band vibrator (Brüel & Kjær type 4810). The results showed that three transposing and three modulating algorithms produced better identification scores than did the filtering algorithm and the unprocessed signal. Two transposing and three modulating algorithms, which were good candidates for implementation in a vibratory aid, were chosen for testing with a portable vibrator (C2 Tactor), which, however, had more limited bandwidth than the stationary vibrator used in the first study (22).

In a second study (23), the five algorithms were tested using the portable narrow-band vibrator in three laboratory experiments. In the first ex-

periment, the 45 environmental sounds (the same sounds as used in the previous study (22)) were preprocessed, recorded and presented off-line. In the second and third experiment, the sounds were reproduced in an acoustic test room, with or without background noise, and processed in real time. The subjects identified the stimuli by choosing one of the 45 event alternatives. The results showed that four algorithms, one transposing and three modulating algorithms, produced equally good scores, and they were chosen as candidates for implementation in a portable vibratory aid to be evaluated under realistic conditions indoors and outdoors. The new contribution in the present study is the use of real environments. One possible draw back of testing in such environments is that confounding factors, such as unplanned events, may interfere.
The specific purpose of this present study was to evaluate a vibrotactile monitoring aid for the deaf and deafblind for detection, identification and directional perception of environmental sounds in a home and in a traffic environment.

Method:
The vibrotactile monitoring aid was tested with equipment identical to that used in the acoustical laboratory (23) in the home and in a traffic environment for detection, identification and directional perception of environmental sounds under two conditions:
The subjects were inexperienced (the events were unknown to them)
The subjects were experienced (they had previously experienced the events), and the aid was in either the on or off position.

Subjects:
Five volunteers (3F/2M) tested the aid (see Table I). They were profoundly hearing impaired or totally deaf, between 22–36 years of age and had participated in the previous studies(22,23). Three of the subjects were using hearing aids and one had a CI. The subjects were not aided during the tests. They had good visual acuity, but were blindfolded during the tests.

Test sounds:
In the present study, important events that each produced a sound were selected and presented a different number of times.
Twelve sounds from events often occurring in the home environment and five sounds often occurring in a traffic environment were used as test stimuli (see Table II). In traffic, the sounds from the events came from different directions.
The sounds were chosen on the basis of studies by Borg et al. (5) and Ranjbar et al. (21). Most of the sounds had been rated by deafblind subjects as representing important environmental events and also by the authors as a relevant sample of ecologically valid environmental events (sounds).

Equipment:
Prior to the current field study, the equipment (see Figure 1) was developed and tested in a series of laboratory studies with a heavy stationary vibrator (22) and a portable vibrator (23). The sounds were picked up by microphones (AKG C 417). The signals were processed in the signal-processing program, Aladdin Interactive DSP 3.0 (in a stationary computer), using a sampling frequency of 8,000 Hz, or when possible 12,000 Hz. The processed signal was sent to the narrow-band vibrator (C2 Tactor) to be identified using the vibratory sense (the spectrum of the vibrator was equalized using an anti-filter according to the data in the manufacture's specification). The vibrations were presented on the thenar eminence and the fingers (using their fingers, the subjects held the vibrator on the thenar eminence) of the dominant hand for identification.
The direction of the event was coded by two vibrators (Coin/Pancake Vibration Motors KE2 684) positioned behind the ears. The three microphones and the two vibrators for directional perception were mounted in a headband.
Different combinations of long/short pulses representing eight different directions (forward, left-forward, left, left-back, back, right-back, right and right-forward) were sent to the two vibrators, which were mounted behind the ears on each side of the headband (see Figure 2). The directions of

the events were presented according to the following scheme:

If both vibrators gave short or long pulses, the sound was from the front or back, respectively.

If the right vibrator emitted two pulses in a sequence like, short short, short long or long long, the sound was from the front right, right or back right side, respectively.

If the left vibrator emitted two pulses in a sequence like, short short, short long or long long, the sound was from the front left, left or back left side, respectively.

Signal-processing algorithms:

Signal processing in the monitoring aid was accomplished using four different algorithms, which had previously been chosen as good candidates for use in a field study. The algorithms are listed in Table III.

In Algorithm TRHA, the eight frequency components with the highest amplitude in the range 100–4000 Hz were transposed to the frequency range 187–437 Hz using approx. 31 Hz between components, Df»31Hz.

In Algorithm AM, a 250 Hz sine signal was amplitude modulated by the envelope of the input signal.

In Algorithm AMMC, the input signal was band-pass filtered (Butterworth three-pole) in six different frequency ranges (120–240, 240–480, 480–960, 960–1920, 1920–3840 and 3840–6000 Hz, respectively). Thereafter, the envelope (extracted by first rectifying and then low-pass filtering at 10 Hz) of the output signal from each filter was used to amplitude modulate sine signals with the frequencies, 55, 105, 215, 335, 445 and 650 Hz, respectively.

The difference between frequency components was chosen to be larger than 30% (Df/f> 30%), as the frequency discrimination Df/f of the skin is about 30% (9,24,25).

In Algorithm AMMC(A), the signal was processed using Algorithm AMMC and also adapted to the vibratory threshold of the skin using the transfer function representing the average vibratory threshold of the skin (the frequencies between 200 and 450 were attenuated while remaining frequencies under 1000 Hz were amplified), in line with Verrillo (26) and Ranjbar (22).

The level of the signal to the identification vibrator was individually adjusted for each subject in the beginning of the tests. The subjects experienced that the level was comfortable and sufficient.

Each subject was tested with a randomly chosen algorithm (one of the four algorithms with highest identification scores in a previous laboratory study (23)), i.e. Subject 4 (S4) with Algorithm TRHA, S1 and S5 with Algorithm AM, S2 with Algorithm AMMC, and S3 with Algorithm AMMC(A).

Procedure:

The design was basically a case study with non-parametric statistical evaluations. It is characterized by a partly double blind design, as the test subjects were unaware of the test conditions and two of the three experimenters (AA and PR) did not know the status of the vibratory aid (on or off). The subjects were provided with written and verbal information about the test procedure. The experimenters PR and CJ gave the verbal information in sign language when it was needed (one subject was a good lip reader and used a hearing aid and one subject could hear while using a CI when receiving the information). The experimenters PR and CJ have several years of experience in sign language.

The vibrotactile aid was tested first in a home and then in a traffic environment. In both conditions, the test consisted of two parts: inexperienced (training part, the sounds were unknown to the subjects) and experienced (main part, the subjects had previously experienced the sounds). In the experienced part, the subjects knew they would be tested on the same events as in the inexperienced part, but they had no written list of the sounds. In the test in traffic in both parts, perception of the events' direction was also included.

In order to determine whether the vibrator caused any differences in detection or identification scores, the vibrator was also tested both in the on

and off position.
The subjects were filmed during the test-sessions as extra documentation to allow close analysis of their responses, in cases of indistinct responding.
In the conversation with the subjects (after they had conducted the tests), they were asked about their attitudes towards the aid.

Tests in a home environment:
Each subject was seated in a relaxed fashion in an unfamiliar kitchen (4mx5m) with her/his eyes blindfolded, wearing the headband and holding the vibrator in her/his dominant hand. All events (see Table II) were conducted inside the kitchen except Toilet flushing and Doorbell signalling twice and someone opening and closing the door, which occurred inside the bathroom with an open door and in the hall, respectively, both almost seven meters from the test room, the kitchen.
Three experimenters (AA, PR and CJ) were involved in the test. Experimenter AA initiated most of the events, Experimenter PR observed the test situation and made some of the sounds. Experimenter CJ controlled the signal-processing program (choosing the relevant algorithm and switching the aid on and off) and signalled to AA or PR to begin each event. PR and CJ, who could interpret sign language, also noted the subjects' responses.
In the inexperienced (training) part, the subjects were informed that they were to sit quietly when AA tapped twice on their leg and to begin signing their detection (by raising their hand) and identification of the event after AA had tapped once. After the subject's response was noted, (s)he was told whether the response was correct or incorrect and what the correct response was (subjects received feedback). The subjects were encouraged to memorize the events, which would be repeated in the experienced (main) part of the test.
In the experienced part, the 12 events from the inexperienced part were presented twice in random order for each subject, once with the vibrator in the on position and once with the vibrator in the off position. Each experimenter had access to the same sound list, but the status (position) of the vibrator (on or off) was only known to CJ. The experimenter and the subject communicated in the same way as in the inexperienced part, but without any feedback. In the experienced test, the experimenters continued to the next event if the subject did not detect an event.
Every test took up to 1 hour and could be interrupted if the subject wished to take a break.

Tests in traffic environment:
Before starting the test, the subjects practiced and learned the eight directional codes. The directions of the events were presented according to a simple scheme with short and long pulses (see section equipment). The sound sources moved from left/right to right/left at different distances from the subject. The events A car driving… and A moped driving… started at 50 m, the event A signalling bike… started at 25 m, and the events A person running… and A talking person walking… started at 15 m distance from the subject. When the event moved from, e.g., left to right, the direction vibrators coded the following sequence: left, left-forward, forward, right-forward and right (see section Assessment and Figure 2). The car used for event A car driving… was a small, quiet car and was driven smoothly.
When testing the aid, the subjects were sitting on a chair, with their eyes blindfolded, near a relatively calm street, which was almost 200 meters away from a freeway. The traffic noise from the freeway varied from 50 to 80 dBA. If there was an unusual or very loud sound in addition to the test sounds, such as from a power lawn mower or a passing train, a break was introduced.
Experimenter AA and four other persons produced the events causing the test sounds. Experimenter PR observed and noted the subject's responses; experimenter CJ also noted the responses and coordinated the tests.
As in the home environment, the subjects were inexperienced or had experience of the events when tested. In the inexperienced part, the subjects were exposed to the events in Table II twice (once from left to right and once from right to

left) and were asked to detect and identify the event as well as to indicate the direction of the event. They received feedback on their response and the correct answer was given.

In the experienced part, four events (A signalling bike, A talking person walking, A person running and A moped driving) were presented at least four times for each subject, two presentations (one from right and one from left) when the vibrator was in the on position and two presentations when the vibrator was off (four events, two positions of the vibrator, two directions = 16 presentations). The event A car driving… was presented 20 times for each subject, 10 times (five from right and five from left) when the vibrator was in the on position and 10 times when the vibrator was off (one event presented five times, two positions of the vibrator switch, two directions = 20 presentations). The total number of presentations in traffic was 36 for each subject, 18 with the vibrator off and 18 with the vibrator on. The events were presented in random order for each subject.

Like in tests in the home environment, each experimenter had access to the same sound list (different for each subject), but the status of the aid (on or off) for every event was predetermined (known only to CJ). The subjects were informed that they had to raise their hand to show that they had detected an event. The subjects were encouraged to use all of their senses (except vision and hearing). After the subject had lowered his/her hand, PR tapped once on him/her, showing it was time for the subject to sign or indicate the identity and direction of the event. When the subject had identified the event and indicated its direction, the experimenter tapped twice on her/him to indicate that (s)he should be prepared to focus on the next event.

When Subject 1 (S1) was being tested it was windy, and therefore a knitted scarf was used to cover the microphones.

When S3 was being tested with the aid in the experienced part in traffic, there were technical problems with the vibrators presenting the directional information, and these observations were excluded. Every test took up to two hours and could be interrupted if the subject wished to take a break.

Assessment:

Both experimenters PR and CJ noted the subjects' answers regarding identification and direction. Two of the three experimenters who evaluated the results were unaware of the status of the vibratory aid (PR and AA). When there were differences in interpretation, the answers were obtained from the videotape.

After completion of all the tests, the three experimenters first judged the responses/statements from the tests individually and then jointly assigned points to the responses. A correct response (detection, identification or direction perception) resulted in one point and an incorrect response resulted in zero points.

A correct detection means that the subjects signed their detection of the events by raising their hand.

A correct identification means that the subjects identified the event exactly (not partly) correct.

A correct perception of the direction means that the subjects could perceive the main direction the event was coming from. For example, each of the responses A car coming from right-back, A car coming from right, or A car coming from right-forward were correct and assigned one directional perception point if the car came from the right.

In the tests in the home environment, six different subsets of scores were assigned/calculated: three detection scores (inexperienced detection score aid on, experienced detection score aid on, experienced detection score aid off) and three identification scores (inexperienced identification score aid on, experienced identification score aid on, and experienced identification score aid off). The maximum number of points for each sub-test was 12. In the experienced part, the guessing probability was 8.3% (one of the 12 events) provided that the subjects remembered all 12 alternatives. Otherwise, guessing probability might have been considerably lower because subjects could guess sounds other than those on the list.

For the test in traffic, detection, identification and directional perception scores were computed separately (see Table IV). The test resulted in nine scores: three detection scores (inexperienced detection score aid on, experienced detection score aid on, experienced detection score aid off), three identification and three directional perception scores (inexperienced, experienced aid on, experienced aid off). The maximum number of points for each variable (detection, identification and direction) in the parts inexperienced, experienced aid on and experienced aid off was 10, 18 and 18, respectively (i.e. the maximum number of points for the variable, e.g., detection in the parts inexperienced, experienced aid on and experienced aid off was 10, 18 and 18, respectively).

In the experienced part, the guessing probability for correct identification of an event was 20% (one of the five test sounds). The guessing probability for correct perception of direction was 37.5%, which was determined by summing up the probabilities for correct perception of events coming from right-back/left-back (one of eight directions, 12.5%), left/right (one of eight, 12.5%) and left-forward/right-forward (one of eight, 12.5%).

For the inexperienced part, no guessing probability is determined because the subjects did not have access to the sound list (unlimited number of possible responses).

Determination of guessing probability when the aid was off was irrelevant, as the subjects were asked for identification/directional perception only if they had raised their hand to sign detection of the events. Otherwise the test was continued with the following event in the sound list.

A descriptive non-parametric statistical analysis was presented.

Results:

Home environment

Vibratory detection and identification scores were calculated for the 12 signal-processed environmental sounds for each subject.

Detection score:

The detection score was 100% for all five subjects in the inexperienced part.

In the experienced part when the aid was on, the detection score for S1, S2, S3 and S4 was 100% and for S5, who did not detect the event Toilet flushing, the score was 92% (11 of the 12 events). The total detection score was 98.3% (59/60, five subjects and 12 events) when experienced and aid on. When the aid was off, the detection scores were 25% (three of the 12 events), 8%, 0%, 0% and 8%, respectively. S1, S2, and S5 could detect the event Opening and closing the door to the kitchen. S1 could also detect the events Coffee maker and Vacuum cleaner.

Identification score:

The subjects' identification scores in the inexperienced and experienced parts of the tests are shown in Figure 3. As seen in the figure, in the inexperienced part (aid on), the identification scores for S1, S2, S3, S4, and S5 were 42% (five of the 12 events), 25%, 42%, 42% and 58%, respectively (median 42%). The corresponding figures in the experienced part, when the aid was on, were 67% (eight of the 12 events), 33%, 58%, 50% and 83%, respectively (median 58%). Thus, all subjects improved with experience (improved by 8-25 percentage units). When the aid was off, the identification scores were 8%, 8%, 0%, 0% and 8%, respectively, and S1, S2, and S5 could identify the event Opening and closing the door to the kitchen.

All subjects performed better when the aid was on than when it was off.

In the experienced part of the test when the aid was on, the subjects' identification results were consistently better than the guessing probability (8.3%).

The events One person talking on the radio, vacuum cleaner, and Telephone signalling four times had the highest identification scores (scores80%, median=80%), while the events Microwave oven, Doorbell signalling twice and someone opening and closing the door, Fire alarm, and Toilet flushing had the lowest identification scores (scores

40%, median=30%).
Confusions of the events in home environment are shown in confusion matrix, Table V.
The events Microwave oven and Fire alarm were confused with each other, and the event Telephone signalling twice and then someone talking was confused with the event One person talking on the radio.

Traffic environment:
The vibratory detection, identification and directional perception scores for five signal-processed environmental sounds were determined by summing up the points of each participant for each part of the test (inexperienced, experienced aid off and experienced aid on) and creating a detection, identification and directional perception score, respectively. The subjects' identification and directional perception scores in the inexperienced and experienced part in traffic are shown in Figure 4.

Detection score:
Both in the inexperienced and experienced part (when the aid was on), the detection score for all subjects, except for S3 in the experienced part, was 100%. The detection score for S3, who did not detect the last presented event, was 94.4% (17 of 18) when experienced. The detection score in total was 98.8% (89/90, five subjects and 18 presentations) when experienced and aid on.
In the experienced part of the test, when the aid was in the off position, the detection score for S1, S2 and S4 was 0%, while the detection score for S3 and S5 was 5.6% (the subjects could detect one of the 18 presentations: A person running).

Identification score:
As seen in Figure 4, the inexperienced identification scores for S1, S2, S3, S4 and S5 were 20% (two of the 10 presentation), 30%, 40%, 40% and 40%, respectively. The corresponding figures in the experienced part when the aid was on were 22% (four of the 18 presentations), 50%, 28%, 44% and 56%, respectively. All subjects had better scores than the guessing probability, 20%, when they were experienced.
In the experienced part of the test, when the aid was in the off position, the identification score for S1, S2 and S4 was 0% (the subjects did not detect any presented event), and for S3 and S5 it was 5.6% (the subjects could identify one of the 18 presentations: A person running).
The identification scores for all experienced subjects (except S3) were better (when the aid was on) than when they were inexperienced (improved by 2-20 percentage units). The scores were also better when subjects were experienced and the aid was on than when it was off.
Subject 5, S5, could identify in detail the events and their direction. For example, the subject said, "first cars reversed, then someone talked and then a moped drove by from right to left".
The events A talking person walking…, A person running…, and A moped driving… had the highest identification scores (scores 50%, median=50%), while the events A car driving…, and A signalling bike moving…had the lowest identification scores (scores40%, median=32%).
Confusions of the events in traffic environment are shown in confusion matrix, Table V.
The event A car driving (50 presentations, 5 subjects and 10 presentations for each subject) was confused with the events A signalling bike moving…, A moped driving… and the event A talking person…. Interestingly, all the presented events were identified a few times as the same event A talking person… (see Table V)

Directional perception score:
As seen in Figure 4, the directional perception scores in the inexperienced part for S1, S2, S3, S4, S5 were 60% (six of the 10 presentations), 40%, 30%, 50% and 50%, respectively. The corresponding figures in the experienced part when the aid was on for S1, S2, S4 and S5, were 67% (12 of the 18 presentations), 83%, 78% and 61%, respectively. The directional perception score for S3 was not determined (due to technical failure).
In the experienced part of the test, when the aid was in the off position, the directional perception score for S1, S2 and S4 was 0% (they did not de-

tect any event), while direction score for S3 and S5 was 5.6% (for one of the 18 presentations, A person running, the subjects could recognize the direction of the event).

The directional perception scores for S1, S2, S4 and S5 were better when the subjects were experienced than when they were inexperienced. The directional scores were improved by 7-43 percentage units and were better than the guessing probability, 37.5%.

Attitudes towards the vibratory aid

In conversations with the participants, they expressed attitudes towards the aid. All of the subjects had very positive attitudes towards the aid and believed it could help deafblind as well as deaf persons. S1, who is a good lip reader, was very optimistic, and one impression was that he sometimes could identify speech with the vibrator in the on position and without lip reading. S4 appreciated the aid a great deal and wanted to use it to identify, e.g., the telephone signal, the doorbell, the alarm clock or to feel music. S1 and S4 only liked the identification part of the aid, because they did not like wearing the headband.

Discussion:

The purpose of the present study was to provide a preliminary evaluation of a tactile aid for the deaf and deafblind for detection, identification and directional perception of environmental sounds in realistic environments. Below, first some aspects of the methods and then the results will be discussed. The results of individual cases are finally treated separately.

Methodological aspects:

Subjects

The subjects were familiar with the vibratory aids, as they had participated in similar tests in previous laboratory studies (22,23). They were few in number, but sufficient for a case study (27).

In some respects, it would have been better to use deafblind instead of deaf and blindfolded subjects, because the vibratory aid is primarily intended as a monitoring aid for the deafblind. However, we had difficulties communicating with deafblind persons (none of us knew sign language for the deafblind). Using interpreters may have made the test time longer, and the procedures may have been exhausting for deafblind subjects. This may have resulted in confounding factors, which, in turn, may have negatively affected the results. On the other hand, deafblind subjects are more used to interpreting vibrations (28,29), and therefore they may have obtained better identification scores. The choice of deaf subjects made the testing technically easier, and decreased the risk of confounding factors. On the other hand it can be assumed that is was harder for the deaf subjects to interpret the vibratory information than it would have been for deafblind persons, who have more experience of using vibrations. In further tests, the fully portable vibrotactile aid will be evaluated by deafblind subjects and use of the aid will include long-term training.

Events:

The present authors and deafblind subjects in the study by Borg et al. (5) selected the test sounds (see Table II) and regarded them as ecologically relevant, and as sounds that signal important environmental information. The sound Doorbell signalling twice … occurred outside the hall and the sound Toilet flushing inside the bathroom with an open door. These events occurred in almost 7 meters from the test room, the kitchen. The sounds had a low intensity level, which caused some difficulties in sensing and identifying them. This was a drawback, but the situation was realistic and therefore included.

Signal processing algorithms:

In the previous laboratory study (23), the four algorithms showed no difference for the present subjects. Therefore the algorithms were assigned randomly to the subjects. The intention of the present study was not to compare the algorithms. In further tests, new algorithms can be developed and tested using a fully portable vibrotactile aid and deafblind participants. Such tests should include long-term training. After training, algorithms that preserve more spectral information (e.g., Algorithms TRHA, AMMC and AMMC(A)) can be expected to produce better scores compared to algorithms with poor spectral information (e.g., Algorithm AM), despite the poor frequency discrimination and resolution of the skin (9,30).

Equipment, design and procedure:

We have found no better small vibrator on the market than the C2 Tactor used in the present study with respect to bandwidth (large bandwidth with minimal peaks) and weight. The wideband vibrator of the type used in our laboratory study (22) weighed 1.1 kg and is obviously too heavy for a portable aid. A small vibrator with an even larger bandwidth than the C2 Tactor would improve the aid and probably improve the effects of training.

The frequency response of the vibrator was equalized using an anti-filter according to the data in the manufacture's specification. The equalization, however, did not sufficiently compensate for the high frequency attenuation of the vibrator.

The sounds from the events were signal processed using a stationary computer, which needed a power supply and thereby limited the choice of test locations. The test environment, both in a home and in a traffic environment, was unfamiliar to the subjects. Use of the same unfamiliar test environments and the same test sounds increased the probability that the participants would have the same baseline knowledge. The scores might have been higher if the tests had been conducted inside or outside the subjects' own homes. We regarded it as impractical and ethically dubious to have at least three strangers in one participant's home, to blindfold her/him and produce events that were outside her/his control.

The study was designed as a partly double blind study. In the experienced parts, only one of the experimenters (CJ) knew the status of the vibrator, on or off. By using a fully double blind design (none of the experimenters know the status of the vibrator), the otherwise undesired subjective components could be further decreased.

Before the test in traffic, the subjects practised the directional code as long as they needed (it took a maximum of 20 minutes to learn). The experimenter evaluated the subjects several times to ensure that they had learned the codes.

The weather conditions were not the same for all subjects. The temperature, wind, etc., which can affect the sensitivity of the skin (9), were not controlled for. Still the situation was realistic, because the user of the aid (e.g., a deafblind person) cannot control the weather conditions. The weather, however, did not differ greatly across subjects. However, after the test session, S1 revealed that it had been difficult to differentiate the wind touching his left cheek from the feeling of the vibrator indicating direction. The test hours were almost identical for all subjects.

The two experimenters PR and CJ, who interpreted throughout the tests, were not professional interpreters, but had good knowledge of sign language. In addition, they worked together and could correct each other, thereby increasing reliability (31). The tests were filmed, and in one case where the experimenters PR and CJ noted different reactions s, the film was used to identify the correct response.

The subjects had better directional scores when they were experienced than when they were inexperienced. This improvement was unexpected, because the subjects already knew the code of the directions. The difference in directional score can be explained by the fact that in the inexperienced part, the situation was new, and the subjects had to focus both on identification and on direction of events. In the experienced part, they were used to the test situation and could more easily focus on two things at the same time. Thereby the direction scores might improve. In the experienced part, the subjects knew that the events moved either from left to right or from right to left (and not, e.g., from front to back). Thus the direction could have been guessed correctly with high (50%) probability. The subjects very seldom described the direction as only being from the left or from the right. They were very detailed and described every presented direction code they sensed, which indicates that they did not guess.

Assessment:

In the tests in traffic, if the correct direction was recognized, the response resulted in one point, otherwise it resulted in zero points, although a background sound from another direction could have caused the subjects to recognize a correct direction for the interfering event (which resulted in zero points) rather than the direction produced by the test event. Giving both alternatives to directional perception (perception of direction throughout the event and perception of where the sound started from) a full point is based on the fact that deafblind persons consider information (warning) about when a person or a vehicle is approaching to be highly important, as such information allows them to move away or stay in a safe position (5).

The guessing probabilities for correct identification of an event in a home and a traffic environment were estimated to 8.3% and 20%, respectively. These values would be correct if the subjects had access to the sound list. Because no lists were used, the guessing values were (considerably) lower, as the subjects may not have remembered all sounds presented in inexperienced part.

The identification results of all five subjects with the aid on both when inexperienced and when experienced were better than the corresponding guessing probabilities. The detection and identification results of all five subjects were also better when they were experienced than when they were inexperienced.

All the subjects had better identification scores in the home than in the traffic environment. The lower identification scores in traffic could depend on several factors. One factor is that the subjects had to focus simultaneously on identifying the event and perceiving the direction of the same event in traffic. This requires greater concentration and training. The second factor was the background noise from the freeway; both the general acoustic interference and other interfering events could have misled the subjects. The subjects could often correctly identify intervening events not belonging to the test protocol. For example, the subjects often identified the sound from the presented event A signalling bike… or A talking person… as the sound from an unexpected car or motorbike from the freeway. The sound from A signalling bike… was lower in amplitude than the sound from the unexpected cars on the freeway, and the lower sound may have been masked. Sometimes the subjects identified an unexpected interfering event prior to the scheduled event, for example cars on the freeway or bird song, and therefore identified a sound direction different from that related to the event setup by the experimenters, and this resulted in zero points.

A third factor was the wind, which increased the noise level and masked the sound of the events. This factor obviously affected S1 more than the others.

Another factor that may also have affected the directional perception results negatively is due to the technical limitations of the directional perception algorithm. It works best when the SNR is higher than 8 dB (19). The sound from the background traffic and wind probably decreased the SNR ratio below 8 dB.

Aspects of the results of the individual participants

Subject 1, S1, had the second best identification results in the home environment, but lowest in the traffic environment. This subject had also obtained high identification scores in previous studies (22,23). The subject was born deaf and was used to hearing aids, probably to the vibrations produced by the low frequency components of the environmental sounds, and was therefore expected to have good results, as in previous laboratory study (23). S1's low identification scores in traffic are probably partly due to the windy weather conditions, which were not totally compensated for by the knitted scarf used to cover the microphones.

Subject 2, S2, achieved better results in traffic than at home. This subject had low, but not the lowest scores also in previous studies, which suggests that she might not have been used to interpreting vibrations. The subject had also better effects of training in traffic than in the home environment. The subject was not used to hearing aids or CI.

Subject 3, S3, had the lowest scores in previous studies, but not in the present study. In the experienced part of the test in traffic, there were technical problems with the vibrators representing direction, therefore the directional perception score of S3 was not calculated. The test could have been repeated, but then the subject would have been more experienced and had a different knowledge foundation (baseline) than the other subjects. The subject did not detect the last-presented event when the aid was on. The test time was longer because the test had been interrupted twice and the subject may therefore have been frustrated and tired. Such factors may explain the lower identification scores for S3 when experienced than when inexperienced.

The scores of Subject 4, S4, were good in the present study, just as in previous studies. No specific reason was found for his good results, but the subject was born deaf and therefore used to vibrations (used to vibrations from hearing aids).

Subject 5, S5, had the best identification scores in the home environment. The subject had high scores in previous studies as well. In the inexperienced part of the test in traffic, the subject identified the events and their direction in detail by responding for example "first cars reversed, then someone talked and then a moped…" (see results section). The subject was correct, because when the vibrator was switched on before the moped started, there were sounds from the freeway, and then a group of birds flew by, which she identified as speech. The subject was skilful (perhaps too ambitious) and explained in detail even though she had been told to focus on the same events as presented in the inexperienced part. Because the subject indicated several directions, it was difficult for the experimenters to decide which direction referred to the direction of the event, and this resulted in zero points.

The subjects differed individually in their results, which can partly be explained by individual properties (motivation, age of onset of deafness, hearing aid use or how used the subject is to vibrations), weather conditions (S1, poor weather) and technical issues (S3). The directional perception algorithm may not generate a 100% correct direction all the time due to disturbing noise (20).

Attitudes towards the vibratory aid

All of the subjects had very positive attitudes towards the aid, even if they had good vision and could compensate for their hearing impairments. They wanted to use the aid to detect events resulting in only sound (and not movement or changes in light), e.g. the telephone signal, the doorbell, the alarm clock or to feel music, in addition to using the vibrations as a complement to lip reading.

S1 and S4 only liked the identification part of the aid. A headband or eyeglasses are needed for mounting the three microphones used to indicate sound direction. A vibrotactile aid with only one microphone placed close to the processor could be designed for subjects who prefer to abstain from the directional information and to only use the information to identify the events. Two alternative designs are therefore likely in the future: one with and one without directional information.

Comparison with other vibratory aids and CI

There are tactile aids available on the market, such as Sentiphone, MiniVib II and Tactaid VII. The main goal of MiniVib II and Tactaid VII is improvement of speech reading and speech perception. However, some test results show that subjects reported more benefit of the aids when identifying environmental sounds than when identifying speech (3,7). This also inspired the present line of research: Designing a vibrotactile aid for environmental sounds, which for many subjects seems to be the foremost benefit of such aids. It is difficult to compare the present results with those on MiniVib II or Sentiphone, as these aids have not been systematically evaluated using environmental sounds and/or they have not been tested under conditions similar to those in the present study.

The vibratory aid Tactaid VII has been tested by Reed and Delhorne (11) using four environmental sound settings (kitchen, home, outdoors and office) and two groups of subjects (normal hearing and profoundly deaf). The tests were conducted in a laboratory using a closed set of 10 sounds, where subjects had access to a sound list (which increases the guessing chance) and were trained on 600 items with feedback. The average results for the profoundly deaf subjects (who are comparable to participants in the present study) was 58%, 59%, 64% and 52% for tests in the general home, kitchen, office and outdoors, respectively. The average results in the general home are equal to the median result in a home environment in the present study (58%), despite the fact that subjects in the present study had trained only once and had no access to the sound list. The monitoring aid in the present study can generate additional directional information that is valuable for deafblind people with small residual visual fields.

A comparison of different tactile aids would be more informative if they were evaluated under similar conditions and if the tests included (long-term) training.

The CI (32-34) also improves the sound monitoring and speech perception of deaf and deafblind subjects, but it requires functioning auditory nerves and surgery. Furthermore, CI are most effective in prelingually deaf subjects if the implantation occurs before the critical period (under 2 years of age) (35) and is combined with post-implantation therapy; time is also required for the brain to adapt to hearing new sounds. In a comparison of CI, tactile aids (Tactaid II) and hearing aids, subjects with early onset deafness (before 2 years of age) who received their CI before 10 years of age showed the highest speech intelligibility scores. Subjects who received their device after 10 years of age had poorer speech intelligibility scores, and there were no significant differences in the speech scores of subjects (with hearing levels between 100 and 110 dB HL and limited hearing in the high frequencies) using CI, tactile aids and hearing aids (36). In a CI study by Reed and Delhorne (34), the identification scores for environmental sounds were related to NU-6 word perception (which in turn was related to, e.g., duration of deafness). Subjects with NU-6 word scores below 34% had greater difficulties (their identification scores for environmental sounds ranged from 45% to 75%) than did subjects with NU-6 word scores higher than 34% (their identification scores ranged from 80% to 94%) when testing four different closed sets of 10 sounds, each representing different environmental situations (general Home, Kitchen, Office and Outdoors). The above results are difficult to compare to the present results, as the tests were conducted under different conditions. Reed and Delhorne's CI subjects had long experience with their aid and had access to a 10-item closed-set sound list during testing, in contrast to the present subjects (37).

Because cochlear implantation has some disadvantages, e.g. there is a risk for Meningitis in patients and the costs are high, implantation might not be considered when the expected result is limited to improved detection of environmental sounds (events). The monitoring aid presented here could be seen as an alternative when cochlear implantation is not feasible.

Features of the sounds

The events One person talking on the radio and Telephone signalling four times, which were signalling or had a typical temporal pattern, were easy to identify, which is compatible with the findings of Shafiro (38) and Reed and Delhorne (11). The event Fire alarm also had a typical temporal pattern, but it was often confused with the event Microwave oven, respectively. The events Coffee maker and Water running, which had similar temporal patterns, were confused with each other.In the traffic, the events A person running… and A moped driving… were easy to identify due to their typical temporal pattern (11). The event A car driving … had unexpectedly low identification scores (see Table V). The low scores can be explained by the fact that the car sound was of low intensity and was therefore often confused with the events A signalling bike moving…or A talking person walking…. It may also imply that the deaf subjects in the present study did not use their sense of smell or draughts when trying to identify the events, as a passing car is likely to cause more odours and draughts than a person passing by on foot or bicycle is. Deafblind subjects might have used their other senses to a greater extent.In general, the temporal pattern of environmental sounds is important to identification of sounds/events. Sounds with a typical temporal pattern are easiest to identify and events with a similar temporal pattern are confused with each other.

Conclusion:

In both a home and a traffic environment, the subjects were able to detect more than 98% of the events when the aid was on, while subjects could detect only one or two of the events when the aid was off. The identification scores for experienced subjects in a home environment and in traffic and their directional perception scores in traffic were consistently better than when they were inexperienced or when the aid was off. The subjects differed individually in their results, but all has positive attitudes towards further application of the aid, and thus the results show the promise of extended application.

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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: Sounds from events used in the tests in a home and in a traffic environment

No.	Sounds from events in home environment	No.	Sounds from events in traffic environment
1	Water running	1	A car driving from left/right to right/left
2	Coffee maker	2	A signalling bike moving from left/right to right/left
3	One person talking on the radio		
4	Microwave oven	3	A talking person walking from left/right to right/left
5	Vacuum cleaner		
6	Doorbell signalling twice and someone	4	A person running from left/right to right/left
	opening and closing the door	5	A moped driving from left/right to right/left
7	Telephone signalling four times		
8	Telephone signalling twice and then some-one talking		
9	Fire alarm		
10	Opening and closing the door to the kitchen		
11	Toilet flushing		
12	Electric hand mixer		

Table III: Brief description of the algorithms

Algorithm	Description
TRHA	TRansposing the eight frequency components with Highest Amplitude in the range 100–4000 Hz to the range 200–440 Hz
AM	Amplitude Modulation of a 250 Hz carrier wave
AMMC	Amplitude Modulation with Multiple Channel
AMMC(A)	Amplitude Modulation with Multiple Channel and Adapted to the vibratory thresh-olds of the skin

Table IV: The flow chart of the study design in traffic. The maximum scores (MS) of the param-eters detection, identification and directional perception, when the subjects are inexperienced and experienced and the vibrator is in the on or off position in traffic.

Test in traffic								
Inexperienced			Experienced					
Detection	Identification	Direction perception	Detection		Identification		Direction perception	
Aid on	Aid on	Aid on	Aid on	Aid off	Aid on	Aid off	Aid on	Aid off
MS=10	MS=10	MS=10	MS=18	MS=18	MS=18	MS=18	MS=18	MS=18

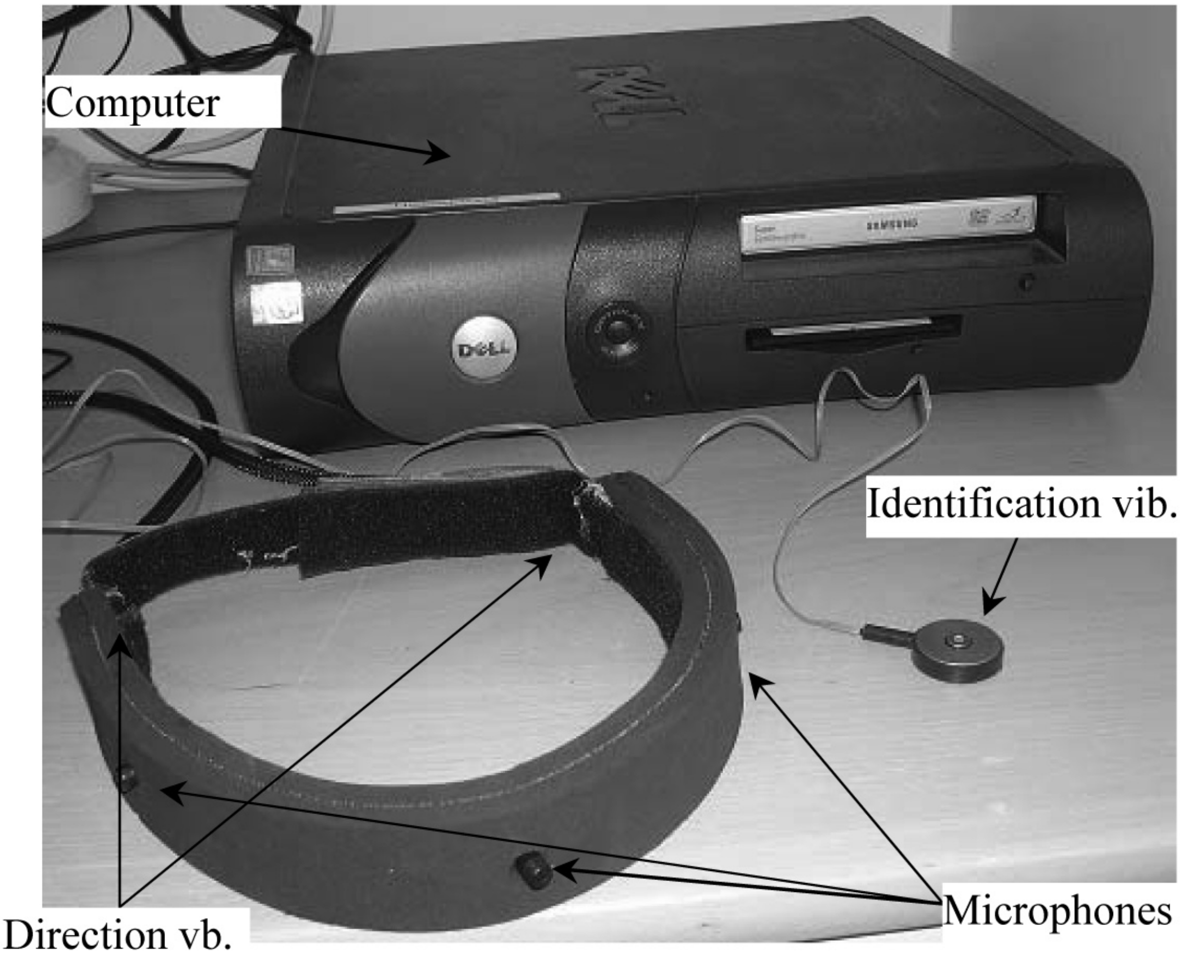

Figure 1: The equipment used in field tests. A computer to process the signal, a headband with three microphones to pick up the sound, and two vibrators for signalling the direction of the sound. A single vibrator that delivers signals for identification of the sound (events) was held in the hand.

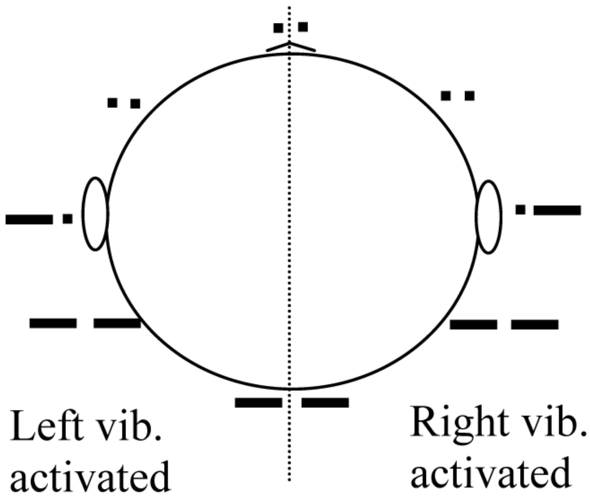

Figure 2: Eight different directions represented by combining long/short pulses from vibrators behind the left and right ear.

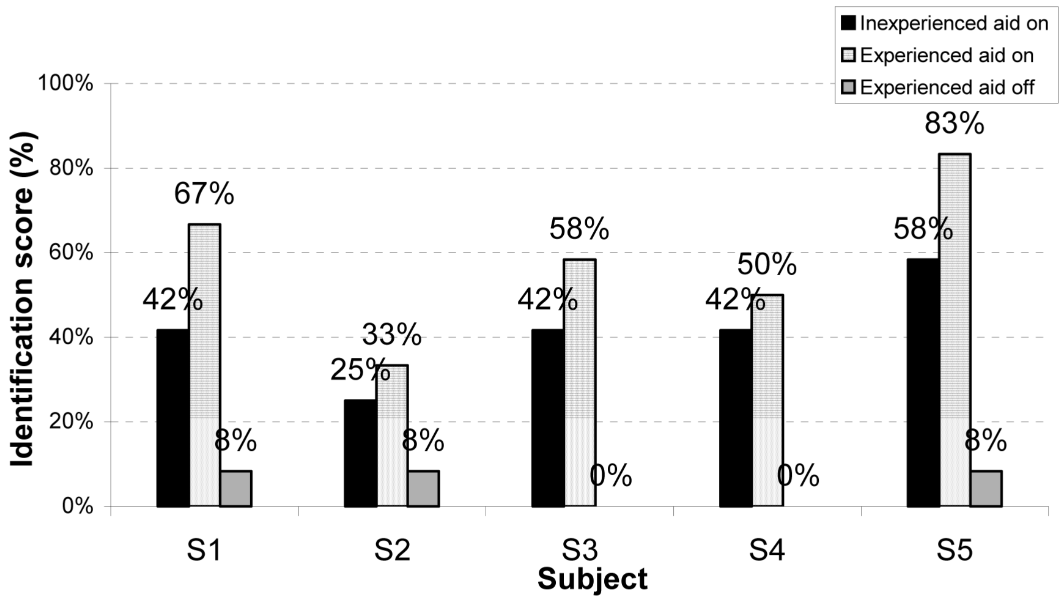

Figure 3: Identification scores for events (sounds) occurring in a home environment for 5 profoundly hearing impaired or deaf subjects. The bars from left to right represent the identification score of subjects when they were inexperienced, when they were experienced and the aid was on, and when they were experienced but the aid was off.

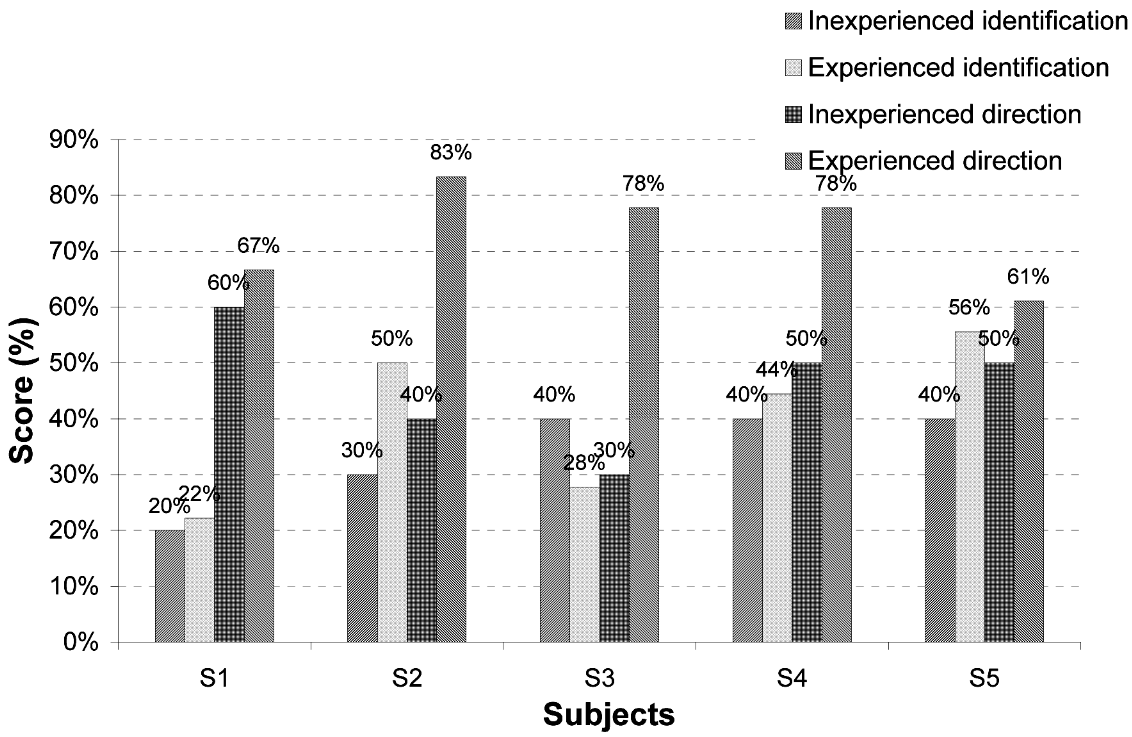

Figure 4: Identification scores for events (sounds) and their direction in traffic for 5 profoundly hearing impaired or deaf subjects using the vibratory aid. The bars from left to right represent the identification scores of subjects when they were inexperienced, experienced and the directional perception scores of subjects when they were inexperienced and experienced. The directional perception score for S3 was not determined (due to technical failure).

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