Speech Intelligibility with a Bone Vibrator

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ABSTRACT

The FELIN project (Foot soldier with Integrated Equipment and Connectivity) of the French DGA (Délégation Générale à l'Armement – French Military Procurement Agency) aims at gearing tomorrow's foot soldier with a "flexible and manoeuvering" equipment. Among requirements, the foot soldier will have to be fitted with a communications headband operating through bone conduction. The main advantage of listening through bone conduction is that it allows for the transmission of information to the soldier, while leaving the soldier's ears free to perceive the surrounding environment and use sound cues for orientation in space. Furthermore, this device is light, not bulky and quite comfortable.

The laboratory assessment performed aimed at comparing voice intelligibility scores of a prototype bone conduction device with the scores obtained by Peltor's® militarized COMTAC-type headset. This latter device is a hearing device, i.e. fitted with two microphones, left and right, to reproduce a spatial hearing capability. It is thus possible to compare these two technologies, which both allow for orientation in space using acoustic cues.

Tests were performed in silence and in operationally realistic noise conditions (reproducing the noisy environment inside an armoured vehicle). Voice material is made of nonsense CVC words (Consonant – Vowel – Consonant), spoken by two speakers of different genders.

In silence, the prototype bone vibrator headband and the COMTAC headset obtain the same intelligibility score. In noise, the performance of the prototype headband is slightly lower than that of the COMTAC headset. A number of reasons can explain this:1) in a noisy environment, finding the right position for the vibrator to get optimal hearing conditions is hard to find. 2) the voice transmission level is too low. It seems that the transmission level is limited because of parasite vibrations which start occurring at high levels.

As a conclusion, bone conduction technology (limited here to "listening") provides a significant positive potential, based on the performance obtained in silence. However, some design improvements must be made to reach levels allowing for intelligibility in noisy environments (notably for use in armoured vehicles).

INTRODUCTION

Project FELIN (Fantassin à Equipement et Liaisons Intégrées – Foot soldier with Integrated Equipment and Connectivity) of the French DGA (Délégation Générale de l'Armement – French Military Procurement Office) is designed to provide tomorrow's foot soldier with a "flexible and manoeuvering" equipment. Among requirements, the foot soldier should be fitted with a communications headband, operating thanks to bone conduction.

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The bone conduction headset (see figure 1) offers three advantages, coming from the fact that ears are left free.

- The soldier's hearing is not jeopardized: weak acoustic signals, like a branch squeaking under an invisible enemy's foot, can be detected; sound sources can be located, and orientation in space remains possible.
- The device is not bulky, and does not prevent from wearing various masks.
- Psychologically, it makes contact with local populations easier.

This study only addresses the "listening" function of the communications headband. Its goal is to validate the technological choice of the communications headband, using intelligibility tests performed in a laboratory. This study is necessary because selecting a technology based on transmission by bone conduction is new for operational applications involving a great number of soldiers.

Testing principles are presented, along with a justification of choices made. After an overview of intelligibility tests, results and answers to questionnaires are then provided and discussed.

1. TESTING PRINCIPLES

1.1 Background

This study aims at comparing the performance of the bone conduction headband with that of PELTOR ®'s COMTAC headset. Both devices make it possible to locate sound sources and hear low intensity sounds.

1.2 Communications Headband (listening function)

Photo 1. Hearing headband in place.

The communications headband uses bone conduction [1] to transmit sounds. A vibrator, made of a electromagnet, controls and moves a small mass placed in contact with the skin. Mechanical vibrations are transmitted through the skin, towards skull bones. Parts of the vibrations are channeled through bone and reach the two cochlea. Distinct signals cannot be applied to each ear, given the high bone conduction speed and the great number of wave propagation channels in skull bones. Another part of the vibrations makes the air in the ear canal resonate, notably if the ear canal is plugged off. Note that vibrators also transmit an acoustic signal, which a priori is not desired, and which is later perceived through air conduction.

The communications headband is made of a metallic arch which makes sure the two electro mechanic vibrators are correctly applied to the zygomatic apophyses of the left and right temporal bones. The arch can be adjusted in length, thanks to a telescopic adjustor. A length-adjustable elastic headband is set on top of the head, to maintain the device in place. The vibrator pads are connected to a small molded casing, placed on the arch, in charge of signal processing.

1.3 Hearing Headset

Photo 2. PELTOR's COMTAC Headset

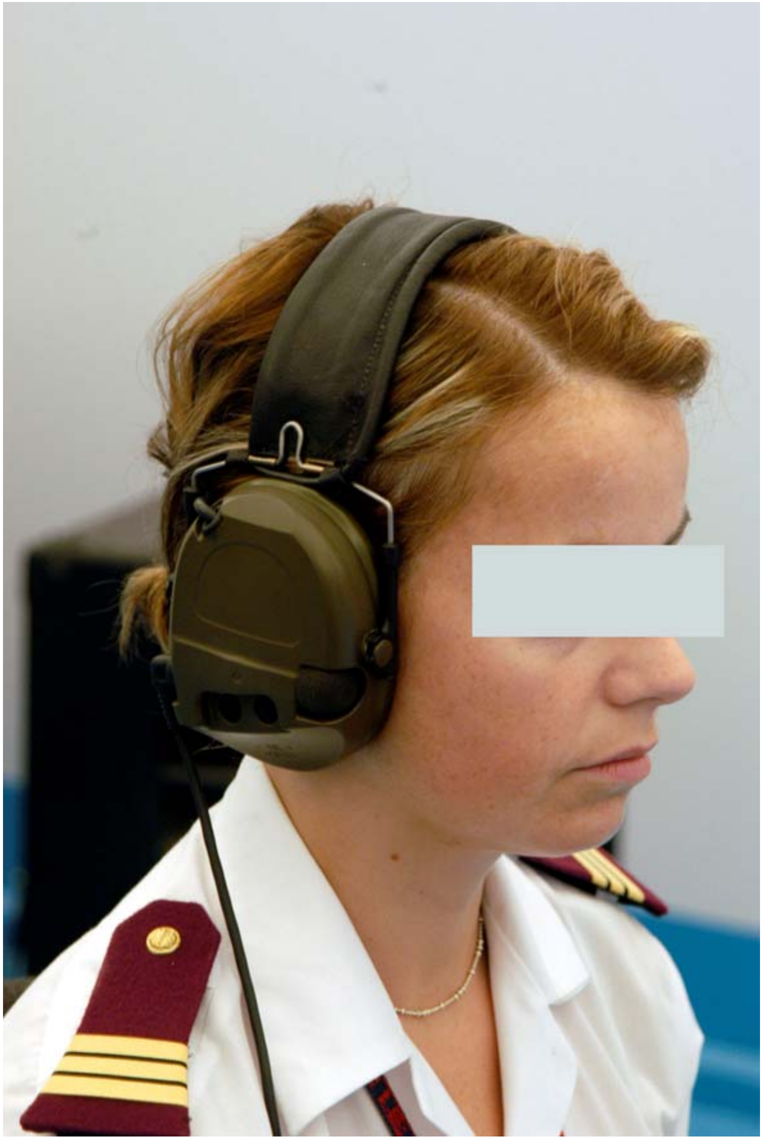


Photo 3. Close-up of PELTOR's COMTAC headset, showing the right microphone coated with anti-wind foam, and the two push buttons used to adjust the sound level for surrounding noise.

The COMTAC hearing headset (photos 2 and 3) is made by PELTOR, and has two miniature microphones, one per earcup. As sound is reproduced and sent to each ear, spatial hearing cues are preserved, allowing to locate the source of ambient sounds. Furthermore, this headset amplifies low intensity surrounding sounds, thus theoretically making the detection of slight noises possible. However, if the sound level is too high, the "hearing" headset becomes "deaf", this headset having a level limiter. When ambient noise increases, the gain of the transmission chain is reduced, to make sure the noise level never exceeds 85dBA. Beyond that limit, there is no longer any gain, and hearing protection becomes identical to that of a traditional passive headset.

Two limitations must be mentioned:

Like in any electronic system, this headset generates a background noise, and the signal to noise (S/N) ratio is often unfavorable for low intensity noises. This headset's performance is below that of natural hearing.

This headset provides poor protection in low frequencies, because of the reduced size of its flat earcups.

This headset is a militarized model, and is standard equipment for French GIPN and RAID forces, for example.

2. BASICS OF INTELLIGIBILITY TESTS [2]

Two kinds of methods can be used to assess intelligibility: objective and subjective methods.

2.1 Objective methods

The best known objective method to measure speech intelligibility is the Speech Transmission Index (STI) [3]. It works by analyzing a test signal obtained at the receiving end of the device under assessment. The STI index is then calculated, according to the deformation and degradation of the test signal in various frequency bands. The STI was validated thanks to a procedure using iteratively physical and subjective measures. A simplified version of the STI, called RASTI (Room Acoustical Speech Transmission Index) has been standardized (IEC268).

This objective assessment method has two specific strong points:

- Measurement "standardization", making it easy to compare two systems. The STI index can be considered as part of a system's characteristics, along with bandwidth, distortion rate, etc.

- Speed. A single measurement is sufficient to qualify the system's intelligibility, which saves a lot of time compared to subjective assessments.

However, this method cannot be used for the bone conduction headband, because the output signal of the device under test must be available. The objective method can be used to assess a headphone, by placing a microphone in the hearer's hearing canal. But there is no output signal available with the hearing headband. It would have to be captured in the cochlea, which is impossible. Some physical measurements of the transducer's properties can be obtained, by installing it on a mechanical mock-up simulating a human head (artificial mastoid), fitted with an accelerometer measuring vibration amplitude. But these measurements do not take into account transmission from the cochlea to the hearer, and only provide data the transducer's manufacturer can use to characterize its device.

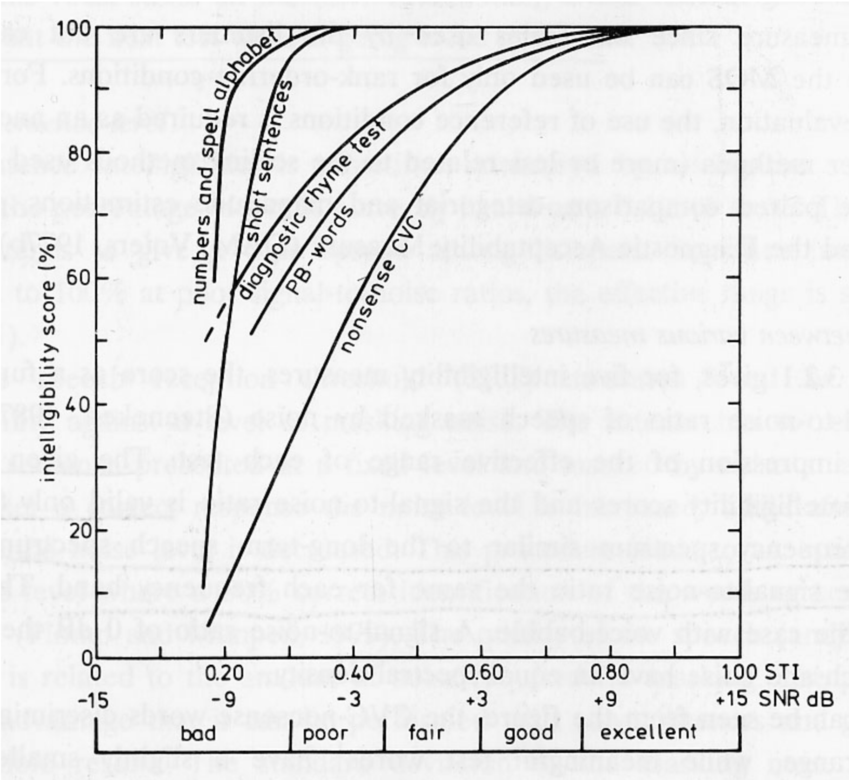
Assessing the intelligibility of an osteophone (bone vibrator) is thus mainly based on subjective tests.

2.2 Subjective methods

During subjective tests, a subject must identify speech transmitted through the device requiring testing. The word "speech" is used deliberately, to be as wide as possible. Intelligibility tests differ according to the nature of the speech transmitted: it can be alphabet letters, figures, words, sentences, various associations of consonants and vowels, or of elementary components of language such as phonemes.

Figure 1 [3] gives intelligibility scores for five kinds of tests, according to the signal to noise ratio of noise-polluted speech. This makes it possible to appreciate the effective dynamic range of each test. On Figure 1, nonsense CVC words (Consonant, Vowel, Consonant) allow for differentiation in a wide dynamic range, whereas PB words (Phonetically Balanced: statistical distribution of phonemes representative of language) offer a narrower dynamic range. Tests with figures and letters show saturation at a –5dB signal to noise ratio, because there are few test words, and identifying them relies mainly on vowel recognition.

Figure 1. Comparison of subjective intelligibility tests (for sounds having a frequency spectrum similar to that of speech - Steeneken, 1992)



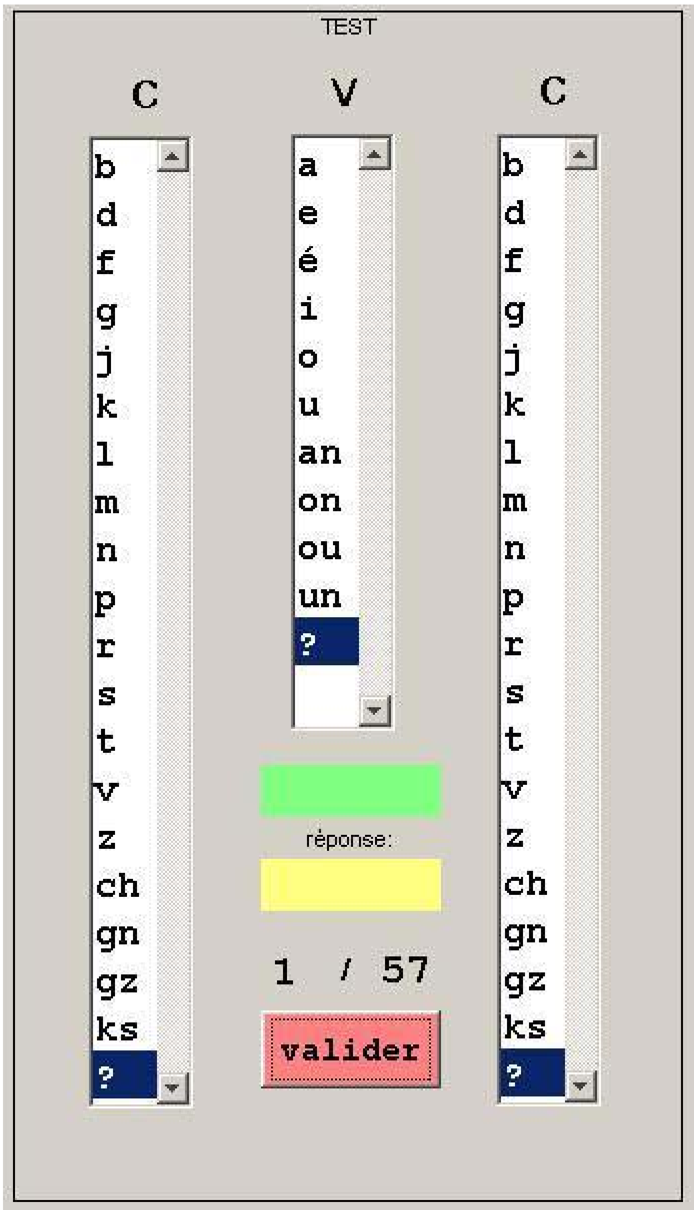
Because of its broader dynamic range, the nonsense CVC test is the best suited test to compare the bone vibrator headband with PELTOR's COMTAC.

3. CVC TEST AT IMASSA

The subjective test used provides for open responses, and for a significant discrimination on a wide range of signal to noise ratios. The listener must recognize a Consonant Vowel Consonant word inserted in a carrier sentence. CVC words are made of initial consonants, vowels and final consonants appearing in spoken language. 19 initial and final consonants were chosen, as well as 11 vowels. CVC words are taken at random, and placed in 57 different carrier sentences. These sentences and the CVCs are recorded and played back using a computerized device. Voice material (3,000 CVC words and 57 carrier sentences per speaker) were recorded by a male speaker and a female speaker during a past experiment ("Study of the architecture and design of a new generation audio system, Contract STTE/AVI n°94/86002).

In practice, the subject, in front of a desktop, listens to recorded speech and used the mouse to click on any recognized CVC phoneme. The visual interface can be seen on Figure 2. This program was developed with Matlab®. The sound is transmitted by a TDT RP2.1 processor, connected to the PC through a USB interface. Excel® is used to process resulting data.

Figure 2 - CVC test visual interface



4. TEST CONDITIONS

4.1 Sound environments

Photo 4. Reverberation chamber

- Measurements in silence are carried out either in the anechoic chamber (below 16 dBA), or in the reverberation chamber (below 27 dBA, with power amplifiers in maximum gain position).

- Measurements in noisy environments are carried out in the reverberation chamber, simulating the ambient sound of an armoured troop carrier vehicle, driving off-road (97dBA).

4.2 Telephone filter

The manufacturer supplies headbands equipped with receiver/transmitter devices. However, our goal is to evaluate the transducers and not the quality of radio-electric transmissions. Consequently, cabling was modified by the supplier.

However, it is normal to test the communication devices in the telephone bandwidth. The two devices were thus tested by inserting a digital telephone filter, integrated into the processor transmitting speech signals. This handicaps the COMTAC headset, which has a wide bandwidth.

4.3 Subjects

Nine subjects performed the test. Tests with a tenth subject had to be stopped, because this person complained of headaches and loss of balance right after the first test with the bone vibrator headband.

Audiogram

Frequencies tested are as follows:

125 – 250 – 500 – 1,000 – 2,000 – 3,000 – 4,000 – 6,000 and 8,000 Hz.

For six subjects, losses are below 15dB, whatever frequency or ear.

For two others, losses reach 20dB for one ear and one frequency.

For the last subject, the right ear is normal (<15dB). For the left ear, losses are 25dB at 3 kHz, 20dB at 4 kHz and 20dB at 6 kHz.

4.4 Selecting the "listening" level

4.4.1 General

Choosing the listening level is critical when listening in a noisy environment. The louder the speech, the better the intelligibility. It is thus important to assess the sound level delivered by each transducer and compare them. To this end, an equivalent sound level must be assessed for each technology. Furthermore, the speech signal is an extremely variable signal, with a transmission level hard to measure. The calibration signal is taken to be the 60 first seconds of the sequence of all CVCs starting with the "p" consonant and spoken by the male speaker.

We must also be careful not to expose our subjects to hearing levels which could jeopardize their hearing, notably during exposure to loud noise. When subjects test the bone vibrator headband in noise, they must wear hearing protection devices, i.e. ear plugs.

4.4.2 Listening level with COMTAC

The listening level with the COMTAC headset is adjusted on an artificial head [4] at 84dBA in noise and at 72 dBA in silence. The equivalent level (free front field) is obtained by withdrawing the FTOE (Fonction de Transfert de l'Oreille Externe – External Ear Transfer Function), i.e. 78 dBA in noise and 66 dBA in silence. Please note that these levels cannot harm hearing.

4.4.3 Listening level with the bone vibrator headband

a. Selecting the electric emission level

At high levels, the headband tested is subject to distortion and vibration. Selecting the emission electric level requires finding a compromise between the listening level, which must be high enough to perceive correctly in noise, and distortion, which must remain low for intelligibility to be preserved.

The maximum emission level we selected for the bone vibrator communications headband was approved by the manufacturer.

b. Problem with measuring the vibration level.

We need to determine the level used by each subject to listen with the bone vibrator headband. This level depends greatly on the pressure applied, on the nature of bone, on the presence of hair, fat, etc. It is thus necessary to evaluate an equivalent acoustic level.

c. Equivalent acoustic level

Given these conditions, we developed a subjective method, making a loudness comparison with a sound transmitted by a loudspeaker placed in front of the subject. This method was first developed by Bekesy in 1949. In silence, the equivalent listening level (in front free-field) ranges from 46 dBA to 56 dBA, depending on subjects, with an average of 51,3 dBA and a standard deviation of 3,6 dB.

In noise, the electric signal is increased by 10 dB. Furthermore, subjects are fitted with earplugs, and the occlusion effect occurs [1]. Sound level is then assessed to be 75 dBA.

4.4.4 Summarized listening levels

Sound level equivalent to front free-field (dBA)	COMTAC	OSTEO (bone vibrator)
Silence	66	estimate: 51
Noise	78	estimate: 75

Table 1: Equivalent sound level in front free-field with COMTAC and bone vibrator

4.5 Protecting subjects from noise

French Law requires limiting exposure to noise. Noise must not exceed 85dBA for a daily exposure of 8 hours, 5 days a week. Beyond 85 dBA, each time the sound level increases by 3 dB, admissible exposure time is cut in half.

In a 97dBA noisy environment, subjects can only be exposed for half-an-hour with the headband, and bare ears. Of course, intelligibility would be zero. For this reason, during tests in noise, subjects are fitted with classic foam Ear® plugs (7/9), or Quies® earplugs (2/9). Under these conditions, our subjects are well protected from noise, and can be exposed to noise up to 4 hours a day.

5. INTELLIGIBILITY MEASUREMENTS

5.1 Test conditions

A training or test session is made up of 57 sentences, each including a CVC word.

Each subject first undergoes five training sessions. The first four are conducted in silence, two with COMTAC, two with the bone vibrator headband. The last session is conducted in noise, with the bone vibrator headband.

Each subject then undergoes eight test sequences:

2 environments (silence, noise)* 2 transducers (Bone vibrator, COMTAC) *2 speakers (male, female). The order of sequences is randomly drawn.

For COMTAC, in silence, the “hearing” function is activated with minimal gain. In noise (moving armoured vehicle), the “hearing” function is cut off.

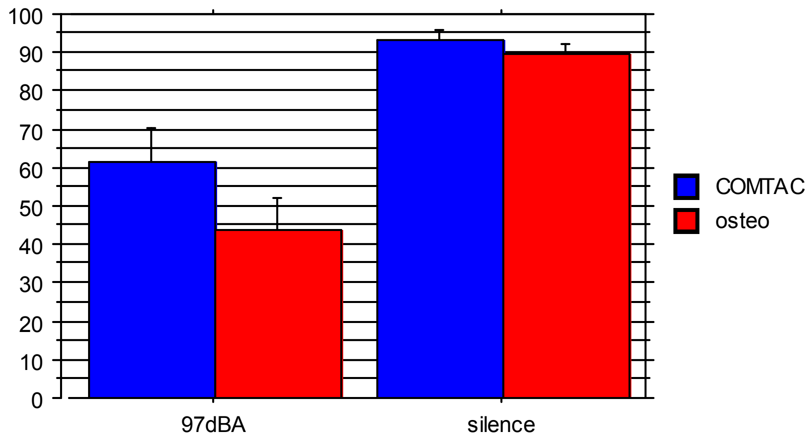
5.2 Results

5.2.1 Overall performance

In silence (figure 3), results are close: 93 ± 5% words are perceived correctly with COMTAC, and 90 ± 5 % with the bone vibrator (significant difference, $p<0,05$). When checking the performance for each C-V-C answer (initial consonant, vowel, final consonant), there is no significant difference between the two technologies.

In noise, the bone vibrator performs more poorly than the COMTAC: 44 ± 17 % versus 62 ± 17 % (significant difference, $p<0,004$). Difference in performance comes from the final consonant. There is no significant difference between the two technologies for the initial consonant and the vowel.

Figure 3. Percentage of words correctly perceived, effect of environment*headset



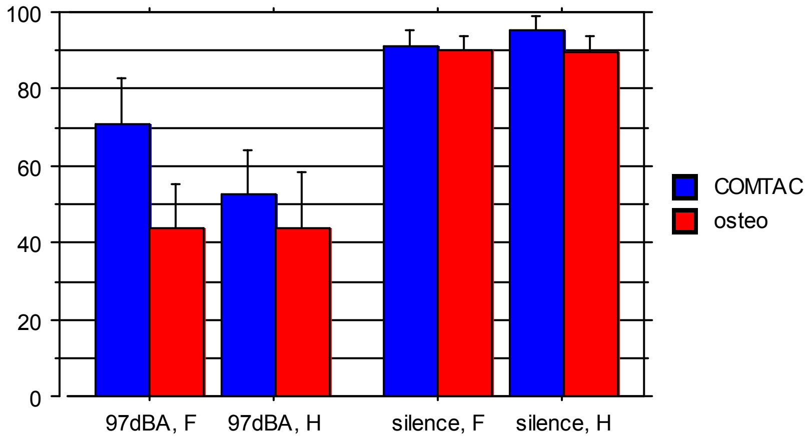
Error bars correspond to a 95% confidence interval

5.2.2 Speaker effect

There is no speaker effect with the bone vibrator (figure 4). In other words, male and female voices are perceived identically.

COMTAC in noise performs better with a female speaker.

Figure 4. Percentage of words correctly perceived, effect of environment*speaker (M/F)*headset



Error bars correspond to a 95% confidence interval

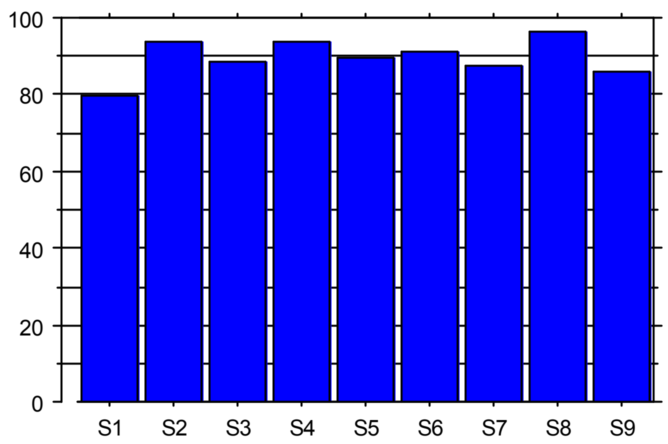
5.2.3 Subject effect

Does performance with the bone vibrator depend on the subject?

Subject effect in silence

There is a statistically significant subject effect (see figure 5), but performance is still above 80%.

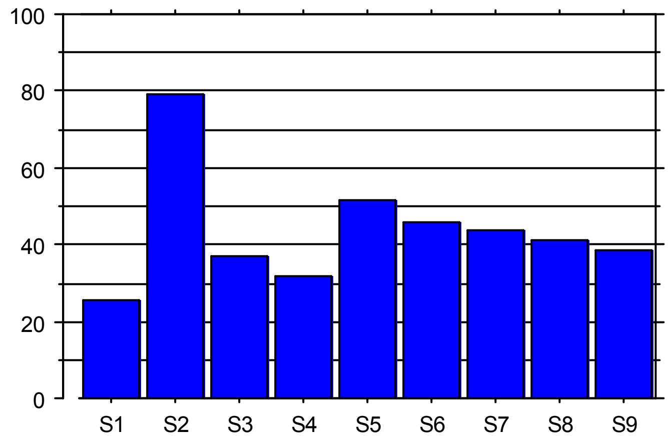
Figure 5. Percentage of words correctly perceived, bone vibrator in silence, subject effect



Subject effect in noise

Subject effect is much greater in noise. Subjects do not all perform identically in noise (see figure 6)

Figure 6. Percentage of words correctly perceived, bone vibrator in noise, subject effect



5.2.4 Summarized results

In silence, both bone vibrator and COMTAC obtain identical intelligibility scores.

In noise, the bone vibrator is not as good as the COMTAC.

With the bone vibrator headband:

- there is no speaker effect
- subjects do not all perform identically, notably in noise.

With the COMTAC,

- there is a speaker effect in noise,
- all subjects perform identically, in silence and in noise.

6. ANSWERS TO THE QUESTIONNAIRE FILLED BY SUBJECTS AFTER TESTS

6.1 COMTAC "hearing" headset

1. Regarding the voice transmission level, would you say it is:

	Too low	Low	Adequate	Strong	Too strong
In silence	0	0	6	3	0
In noise	0	2	7	0	0

The majority of subjects find the transmission level adequate. However, 3/9 subjects find the volume loud in silence.

2. Regarding outside noise perceived, would you say it is:

Not much nuisance	A little nuisance	Nuisance	Great nuisance
1	4	4	0

Overall, noise is considered as being a nuisance. However, this nuisance is moderate.

3. Regarding finding a comfortable listening position, would you say it is:

Very easy	Easy	Adequate	Difficult	Very difficult
4	3	2	0	0

Fitting the COMTAC headset is considered easy, or very easy.

4. Regarding voice quality, could you say it is:

Very good	Good	Average	Poor	Very poor
1	7	1	0	0

A majority of subjects considers voice quality to be good.

5. During or after the test with this headset, did you get a headache or did you feel dizzy ?

No	Yes
9	0

Among the nine subjects tested, none felt any side effects with the COMTAC headset.

6.2 Bone vibrator with earplugs

6. Regarding the voice transmission level, would you say it is:

	Too low	Low	Adequate	Strong	Too strong
In silence	0	0	9	0	0
In noise	2	4	3	0	0

In silence, the transmission level is considered as adequate. However, in noise, the transmission level is considered to be insufficient.

7. Regarding outside noise perceived, would you say it is:

No nuisance	Slight nuisance	Nuisance	Great nuisance
1	4	3	1

Overall, noise is considered as a nuisance. However, the nuisance remains moderate, in general. Noise is only considered to be a great nuisance once.

8. Regarding voice quality, would you say it is:

Very good	Good	Average	Poor	Very poor
0	4	4	1	0

Voice quality is not considered as good as with the COMTAC headset, but it remains good or quite good on average.

9. Regarding finding a comfortable listening position, would you say it is:

Very easy	Easy	Adequate	Difficult	Very difficult
0	1	3	4	1

For a small majority, finding a comfortable listening position is considered difficult. It seems to greatly depend on subjects' morphology.

10. Regarding the possibilities of adjustment provided on the metallic headband, would you say it is:

sufficient	Adequate	Not sufficient	I don't know
2	4	2	1

The metallic headband's adjustment possibilities were considered as insufficient twice. This number is high, given the number of subjects in test. This judgment is highly dependent on the difficulty the subject had in fitting the headband to his/her morphology.

11. Regarding fitting the elastic headband tightly on the head, would you say it is:

Not tight enough	Adequate	Too tight	I don't know
5	4	0	0

A majority of subjects considered the headband not tight enough.

12. In loud voice levels, have you felt vibrations in the headset ?

	Never	Sometimes	Often	Very often
In silence	4	4	1	0
In noise	2	7	0	0

A majority of subjects felt vibrations in silence, and mainly in noise.

13. If you felt vibrations, would you say they were:

	Not a great nuisance	A nuisance	A great nuisance
In silence	4	2	0
In noise	4	3	0

Vibrations felt were considered not a great nuisance, or a nuisance.

14. During loud voice levels, did you feel twitching?

	never	sometimes	often	Very often
In silence	7	1	1	0
In noise	6	3	0	0

A number of subjects felt twitching, especially in noise.

15. If you felt twitching, would you say it was:

	Not a great nuisance	A nuisance	A great nuisance
In silence	1	1	0
In noise	1	1	1

Twitching seemed to be quite a nuisance.

16. During or after the test with the hearing headset, did you get a headache or did you feel dizzy?

No	Yes
9	0

None of the nine subjects felt any headaches or dizziness after the tests.

6.3 . Miscelleaneous

17. Regarding the attention required for the test, would you say it is:

	Greater with the hearing headset (COMTAC)	Greater with the headband (Bone Vibrator)	Identical for the two devices
In silence	0	5	4
In noise	0	8	1

In silence, a small majority considered the test with the bone vibrator to require more attention than with the other device.

In noise, almost all subjects considered the test with bone vibrator to require more attention. The subject who considered that the two devices required the same attention level is the one which scored very high when testing the bone vibrator in noise.

7. DISCUSSION ON INTELLIGIBILITY RESULTS AND ON ANSWERS TO THE QUESTIONNAIRE

7.1 Intelligibility in silence

Intelligibility is good in silence for both technologies (90% with the bone vibrator, 93% with COMTAC). In silence, the bone vibrator performs almost as well as the COMTAC. The difference in listening level (51dBA for bone vibrator vs. 66 dBA for COMTAC, see §4.4.4) probably helps making the COMTAC more intelligible. 3/9 subjects find the COMTAC's level "strong", and 9/9 find the bone vibrator's level "adequate".

As a technology, bone conduction seems to be a suitable choice.

7.2 Intelligibility in noise

In noise, intelligibility is more degraded with the bone vibrator than with the COMTAC (44% intelligibility with bone vibrator vs. 62% for COMTAC).

The lower scores obtained with the bone vibrator have various explanations:

- Our psychological and physical assessment shows a 3dB difference between listening levels in noise (78 DBA for COMTAC vs. 75 dBA for the bone vibrator, see §4.4.4). This is confirmed by subjects who declare that the bone vibrator's listening level is low (4/9) or too low (2/9). Using Steeneken's intelligibility curves (figure 2) [3], it seems that intelligibility drops down to a mere 40% after a -3 dB drop in the S/N ratio occurring around the operating point corresponding to 60% CVC intelligibility. Our results therefore seem consistent; the intelligibility loss observed may come from the listening level being too low. 7/9 subjects found the listening level with the bone vibrator low or too low. Electrically, it is possible to send more energy into the transducer. Unfortunately, this transducer then sends out parasite vibrations. The level used in the experiment, which is a compromise, was agreed upon together with the manufacturer.

- Fitting the device into the right position was difficult or very difficult for 5/9 subjects.

During the learning phase, the subject is taught how to position the headband, while listening to a continuous flow of words. The last training session is done in noise, with the headband. Results were always satisfactory. During the actual test session, CVCs are randomly selected, and the procedure aiming at adjusting the headband position was limited to the first five sentences of the session. These sentences, intertwined with silence, are not well suited to an adjustment phase. In these conditions, two subjects performed much worse in noise than during the learning phase. These sessions were not taken into account, and were repeated after the subjects were able to properly adjust the headband with a continuous flow of words.

Finding the right position can only be done by ear, and only if a continuous flow of words can be listened to. These conditions might be hard to meet in operations.

More adjustment possibilities should be available. 5/9 subjects find the headband too loose. However, even though it was not asked in the questionnaire, subjects clearly only want the headband to be tighter to improve its effectiveness in noisy environments.

It is important to note, that for at least one subject, placing the vibrating surface in contact with the zygomatic apophyses was extremely difficult.

7.3 Drawbacks of the Communications Headband (Bone vibrator)

* Listening with the bone vibrator requires more attention than with the COMTAC (8/9 subjects). This can be linked to the fact that 8/9 subjects find voice quality good or very good with COMTAC, whereas only 4/9 consider it satisfactory with the bone vibrator. The bone vibrator's reduced bandwidth and distortion are probably to blame. The listening level, which is too low, probably also negatively influences subjects.

* Even in test conditions when vibrations are moderate, they were felt by all subjects. However, only 3 considered them to be a nuisance.

In today's development phase of the mock-up device, 2 subjects felt twitching.

At loud level, test subjects felt a muscular contraction, called fasciculation. It is impossible to say whether fasciculation, which is a nuisance, comes from the amplitude of useful vibrations or from parasite vibrations.

* Out of the 9 people who performed the entire test, none experienced any headache or dizziness. The tenth subject felt bad after his first sequence with headband n°2 (the one with a difference in level between the right and the left channel). This person usually suffers from motion sickness. Tests were not continued.

It will be necessary to make sure that the proportion of people suffering from this kind of ailment is low.

CONCLUSION

Our conclusions only address the acoustic and technical aspects of the “listening” function.

In silence, intelligibility is identical with the bone vibrator as with the control system (COMTAC).

However, in noise, intelligibility is more seriously degraded with the bone vibrator than with the COMTAC

A number of reasons can explain this:

- the voice level is too low, because at high level, the transducer starts vibrating.
- it is difficult to properly position the bone vibrator to obtain optimal perception conditions.

In brief, bone conduction technology (reduced here to the mere listening function) has an appreciable initial potential, based on the performance obtained in silence. However, design improvements will be needed to reach the voice levels required for intelligibility in loud environments (notably for use in armoured vehicles).

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