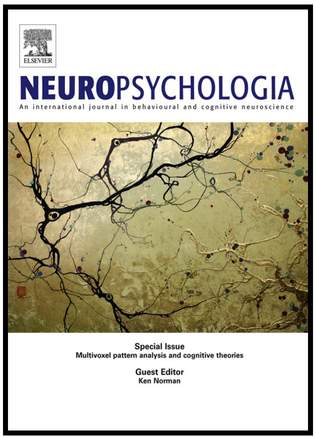

www.elsevier.com/locate/neuropsychologia

# Speech-in-noise perception in unilateral hearing loss: relation to pure-tone thresholds and brainstem plasticity

Nicolas Vannson, Chris J. James, Bernard Fraysse, Boris Lescure, Kuzma Strelnikov, Olivier Deguine, Pascal Barone, Mathieu Marx

PII: S0028-3932(17)30225-7
DOI: http://dx.doi.org/10.1016/j.neuropsychologia.2017.06.013
Reference: NSY6394

To appear in: *Neuropsychologia*

Received date: 5 October 2016
Revised date: 27 February 2017
Accepted date: 12 June 2017

Cite this article as: Nicolas Vannson, Chris J. James, Bernard Fraysse, Bori Lescure, Kuzma Strelnikov, Olivier Deguine, Pascal Barone and Mathieu Marx Speech-in-noise perception in unilateral hearing loss: relation to pure-ton thresholds and brainstem plasticity, *Neuropsychologi* http://dx.doi.org/10.1016/j.neuropsychologia.2017.06.013

# Speech-in-noise perception in unilateral hearing loss: relation to pure-tone thresholds and brainstem plasticity

Nicolas Vannson[a, b,d], Chris J. James [c, d], Bernard Fraysse[c], Boris Lescure[c], Kuzma Strelnikov[a, b,c], Olivier Deguine[a, b,c] , Pascal Barone[a, b*1], Mathieu Marx[a, b, c1]

[a]Université de Toulouse; UPS; Centre de Recherche Cerveau et Cognition; Toulouse, France

[b]CNRS; CerCo; France

[c]Service Oto-Rhino-Laryngologie et Oto-Neurologie, Hôpital Purpan, Toulouse, France

[d]Cochlear France SAS

[*]Corresponding author. CerCo – CNRS UMR 5549, CHU Purpan – Pavillon Baudot, BP 25202, 31052 Toulouse. pascal.barone@cnrs.fr

## ABSTRACT

We investigated speech recognition in noise in subjects with mild to profound levels of unilateral hearing loss. Thirty-five adults were evaluated using an adaptive signal-to-noise ratio (SNR50) sentence recognition threshold test in three spatial configurations. The results revealed a significant correlation between pure-tone average audiometric thresholds in the poorer ear and SNR thresholds in the two

---

[1] Equal contribution.

conditions where speech and noise were spatially separated: dichotic – with speech presented to the poorer ear and reverse dichotic – with speech presented to the better ear. This first result suggested that standard pure-tone air-conduction thresholds can be a reliable predictor of speech recognition in noise for binaural conditions. However, a subgroup of 14 subjects was found to have poorer-than-expected speech recognition scores, especially in the reverse dichotic listening condition. In this subgroup 9 subjects had been diagnosed with vestibular schwannoma at stage III or IV likely affecting the lower brainstem function. These subjects showed SNR thresholds in the reverse dichotic condition on average 4 dB poorer (higher) than for the other 21 normally-performing subjects. For the 7 of 9 subjects whose vestibular schwannoma was removed, the deficit was no longer apparent on average 5 months following the surgical procedure. These results suggest that following unilateral hearing loss the capacity to use monaural spectral information is supported by the lower brainstem.

**Keywords**

binaural hearing, speech-in-noise, vestibular schwannoma, unilateral hearing loss, neural plasticity, pure-tone audiometry

## 1. INTRODUCTION

In listeners with two normal healthy ears (NHL) speech recognition performance depends both on the level of speech and background noise (signal-to-noise ratio, SNR) as well as the spatial separation of target speaker and noise source (Levitt & Rabiner, 1967; Durlach & Colburn, 1978; Steven Colburn et al., 2006; Avan et al., 2015). Indeed, binaural hearing yields different cues necessary for localization of the sound source and optimization of the SNR, which are not available in case of monaural hearing. Binaural hearing facilitates speech recognition in noise allowing the segregation of sound sources from competing noise via three mechanisms: I) binaural summation (or redundancy), II) release from masking or "squelch" effect and III) the head shadow effect. Inter-aural time (ITD) and level (ILD) differences are produced when a sound originating from a given spatial location in the horizontal plane does not reach the two ears simultaneously (ITD) or with the same amplitude (ILD). The integration of ITD and ILD by brain structures is crucial to localize sound sources in space or to segregate target speech in an adverse listening environment such as the ubiquitous "cocktail party" (Cherry, 1953).

Neuronal sensitivity to ILD and ITD has been observed all along the central auditory pathway from the lower brainstem (Pons) to the auditory cortex (Grothe et al., 2010). The superior olivary complex (SOC) in the caudal pons is the first relay of convergence of inputs from both ears. Indeed ILD and ITD are processed by the lateral superior olive (LSO) and the median superior olive (MSO) respectively (Grothe et al., 2010); Davis, 2005). After this low-level auditory processing involving many ascending pathways, inter-aural cues converge to the inferior colliculus (IC) which is a key neural station for binaural speech processing and sound localization (Litovsky et al., 2002; Grothe et al., 2010; Moore D.R., 1991).

In cases of unilateral hearing loss (UHL) the neuronal mechanisms that support ILDs and ITDs are differently altered according to the severity of the deafness. Through neuronal plasticity mechanisms, the peripheral alterations have further repercussion on higher auditory centers involved in binaural processing. Indeed, neuroimaging studies reveal that unilateral deafness is accompanied by central auditory reorganization; patterns of brain activity in UHL subjects stimulated in the preserved ear are different to those observed in monaurally stimulated normal hearing subjects (Ponton et al., 2001; Scheffler et al.,1998; Bilecen et al., 2000; Langers et al., 2005). Indeed, profound UHL induces a shift of activation in contralateral auditory cortex towards more symmetrical activation when a sound is presented to the preserved ear. Interestingly, while most of these changes have been observed at the level of the auditory cortex, no functional reorganization has been reported at the subcortical levels after acquired unilateral auditory deprivation (Langers et al., 2005). However brainstem and midbrain plastic reorganization may occur in case of congenital unilateral deafness (Vasama et al., 1995).

In animal models of unilateral partial or total hearing loss, functional reorganization is reported at both subcortical and cortical levels (Moore & King, 2004; Syka, 2002). Within the brainstem, UHL induces an increase of axonal projections from the cochlear nucleus to the inferior colliculus ipsilateral to the intact ear (McAlpine et al., 1997; Popelar et al., 1994). Further plastic reorganization affecting aural preferences are observed at the level of the inferior colliculus (Moore, 1994) and at the cortical level in the primary auditory field, showing increased ipsilateral activation, especially following early monaural deprivation (Kral, 2013; Kral et al., 2013).

In subjects with unilateral hearing loss, access to ILDs and ITDs is obviously disrupted and localization of the sound source is impaired. Likewise, binaural advantages for speech recognition in the presence of competing noise are missing (Bronkhorst & Plomp, 1989; Munro, 2008). Therefore, subjects with UHL have difficulty in understanding speech in noisy environments, with higher SNRs required to understand speech (Firszt et al., 2015; Rothpletz et al., 2012; Vannson et al., 2015; Giolas & Wark, 1967; Munro, 2008), as well as a reduced ability to localize sounds in space (Slattery & Middlebrooks, 1994; Van Wanrooij & Van Opstal, 2004). Nevertheless, some UHL subjects may partially compensate for these deficits by improving their use of monaural spectral cues. These cues rely on the modifications of the spectral shape of the sounds due to the presence and transfer of the head, and pinna and are mainly processed in the dorsal cochlear nucleus (DCN) (Davis, 2005). In addition, UHL subjects may learn that sound intensity is perceived louder when it comes from the hearing side which may facilitate lateralization in some situations (Van Wanrooij & Von Opstal, 2004; Perrett & Noble, 1995). In spite of these compensatory strategies, UHL remains an established handicap, and deficits for localization and speech recognition in noise have a negative impact on global quality of life (Vannson et al., 2015).

Although standard clinical pure-tone audiometry measures loss in auditory thresholds accurately, it may not correlate with poorer speech recognition in noise as encountered by unilateral hearing loss listeners in daily life (Giolas & Wark, 1967; Smoorenburg, 1992). For example pure-tone average (PTA) thresholds (0.5, 1, 2 & 4 kHz) are not sensitive enough to predict accurately the general SNR loss in a condition where speech and noise are competing (Killion & Niquette, 2000) or to reveal any central reorganization after unilateral auditory deprivation (Maslin et al., 2015). However, in a previous study we have shown that poorer speech recognition in a sound field with spatially separated speech and noise (Vannson et al., 2015) is correlated with lower quality of life for UHL subjects and that the impact increases with the degree of PTA hearing loss in the impaired ear.

Based on these results, the goal of the current study was to investigate within a population of adult UHL subjects the relationship between PTA hearing loss and speech recognition in noise in emulated natural listening conditions. We used the standardized adaptive French Matrix test developed by Jansen and colleagues (2012) in three different sound-field listening conditions to evaluate binaural hearing mechanisms.

## 2. MATERIALS AND METHODS

This study was conducted according to the principles stated in the Declaration of Helsinki (2013) and IRB approval was obtained from the Comité de Protection des Personnes du Sud Ouest et Outre-Mer IV (N° CPP14-021/2014-A00498-39)

### *2.1 Subjects*

Thirty-five adults (19 females) with a unilateral hearing loss were included. All subjects were native French speakers: mean age 47 years, range 25-67. Demographic individual information and hearing characteristics are listed in detail in Table 1. The only inclusion criterion was hearing loss in one ear and normal hearing in the other ear defined by pure-tone hearing thresholds <20 dB HL for octave frequencies between 125 Hz to 8 kHz. Fourteen of the UHL subjects presented a hearing loss in their right ear, twenty-one in their left ear. Group mean pure-tone average (PTA) threshold (0.5, 1, 2 and 4 kHz) in the poorer ear (PE) was 56 dB HL (SD ± 27.27) and 11 dB HL (SD ± 6.98) in the better ear (BE). None of the UHL subjects were equipped with hearing aids or other hearing rehabilitation devices. Eleven NHLs (3 males and 8 females) were recruited as controls (see table 1). The mean age of NHLs was 40 years (range 29-61) and was comparable to the UHL group (bootstrap confidence intervals, p>0.05). PTA thresholds for NHLs were not significantly different to those for the better ear of the UHL subjects (mean difference of 3 dB HL, bootstrap confidence intervals, p>0.05).

### *2.2 Procedures*

Pure-tone air-conduction thresholds were measured with a GN Otometrics Madsen Itera 2 audiometer and TDH-39 headphones for all octave frequencies from 250 to 8000 Hz. Bone conduction thresholds were measured with the same audiometer with a B-71 vibrator placed on the mastoid for frequencies 250 to 4000Hz. The standard clinically used French dissyllabic Fournier word lists were used to measure speech reception thresholds (SRT) in quiet; the level in dB HL being obtained for 50% correct score.

Speech recognition in competing noise was measured using the French Matrix test (Jansen et al., 2012) in sound field (IAC 120A-1 sound booth). The French Matrix test is a closed-set sentence test that uses 50 well-known words in French. Each sentence has the same syntactic structure: name - verb - number - object – color, for example: “Felix draws six blue bikes”. The number of combinations of five words is large enough to avoid any repetition of a sentence and thus substantially eliminates memory-based responses. Speech and noise signals were generated from an IBM PC running the OMA software (www.hoertech.de) and presented via loudspeakers and amplifier (Studio Lab, SLB sat 200). Speech was presented at fixed level of 65 dB SPL (fast) and the level of competing noise was adjusted using the adaptive procedure described by Jansen et al (2012) to obtain the SNR for 50% correct word recognition (SNR50).

SNR50 was obtained in three different spatial configurations: One with speech and noise presented from a single loudspeaker in front of the subject at 0°

and two conditions with speech and noise presented from separate loudspeakers at 60° to the left and right of the subject. The choice of a spatial configuration (-60°, 0° and +60°) was selected based on previous results (Ching et al., 2004) showing that when such positions are used, the head-shadow effect is reduced compared to ±90° whereas the binaural squelch is maximized. For instance, in this type of listening configuration, when the noise is presented to the left ear and the signal to the right one, two different SNRs are created at each ear providing thus a benefit on average of +8 dB SNR at the right ear and –8 dB SNR at the left one (Ching et al.,2004). Therefore, the listener is able to direct his/her attention towards the best SNR. The “dichotic” condition ($\mathbf{S_{PE}N_{NE}}$) was defined as speech presented to the poorer hearing ear (PE) and the noise to the contralateral, normal hearing ear (NE); the diotic condition ($\mathbf{S_{front}N_{front}}$) with both the signal and the noise presented from the loudspeaker located in front of the subject; and the reverse dichotic condition ($\mathbf{N_{PE}S_{NE}}$) with speech presented to the normal hearing ear and noise to the poorer ear. Subjects were asked to repeat any words that they heard.

Speech recognition and pure-tone audiometry was performed on normal-hearing control subjects (NHLs) in two conditions: with both ears open and with one ear plugged to emulate a hearing loss. The earplug (3M - 1100) simulated on average a PTA hearing loss of 35 dB HL (SD ± 3.45). The plugged ear was randomly chosen across NHLs (5 on right, 6 on left ears).

### *2.3 Data Analysis*

Data were not normally distributed, which was confirmed by Kolmogorov-Smirnov tests. Thus comparisons between NHL and UHL were made using a non-parametric, bootstrap technique to generate 95% confidence intervals (1000 samples; bias corrected and accelerated confidence intervals; alpha = 0.05 (Carpenter & Bithell, 2000). The effect size (Cohen's *d*) was computed for significant factors.

## 3. RESULTS

Group summary results for SNR50 for NHLs and UHLs are given in Table 2 for dichotic, diotic and reverse-dichotic presentation conditions. There were no significant differences between mean SNR50 for dichotic and reverse dichotic conditions with both ears open for NHLs (speech right -9.92 dB, ± 1.60 vs speech left -9.25 dB, ± 1.45, $p>0.05$) and therefore SNR50s were combined together (-9.59 dB, ±1.53). The diotic presentation condition produced higher SNR50 for NHLs with a mean of - 4.98 dB (SD ±0.78).

Plugging one ear in NHLs produced higher SNR50s in the dichotic (-4.42 dB, ±3.08) listening condition only (bootstrap, $p<0.05$). However in reverse dichotic, when the speech was presented toward the unplugged ear, SNR50s were similar to that observed in the binaural situation (-9.13 dB, ± 1.51, bootstrap, $p>0.05$).

Unilateral hearing loss subjects presented a deficit for speech recognition in noise in all three listening conditions: Compared to NHL tested in binaural conditions, UHLs had significantly poorer (higher) SNR50s in the dichotic condition (Table 2). This corresponded to significant mean differences between UHL and NHL binaural groups of 8.55 dB (*d* = -2.48) for dichotic, 2.74 dB (*d* = -1.44) for diotic and 2.61 dB (*d* = -1.11) for reverse dichotic conditions. Compared to NHL tested in the ear-plug condition, UHLs also presented a significant deficit in both dichotic and diotic conditions. The deficit of UHL subjects in the reverse dichotic condition was lower than in the dichotic condition likely due to the presentation of the signal to the better ear and the noise to the impaired one.

In order to investigate the relationship between hearing loss assessed by pure-tone audiometry and speech-in-noise recognition, PTA threshold (average 500, 1k, 2k and 4kHz) were plotted against the SNR50 in both dichotic and reverse dichotic conditions for the UHL population (figure. 1A). A filled bold red line indicates the mean SNR50 (-9.25 dB) observed in the NHL population and the two red dashed lines correspond to two standard deviations from the mean (-12.16 dB and -6.34 dB respectively). Values poorer (i.e. higher) than -6.34 dB SNR were arbitrarily considered as deficient as none of the NHL values were poorer (higher) than this. Because values obtained from the two ears for each individual are not necessarily independent, we performed correlation analyses for the two data sets.

Firstly, we observed a correlation (Spearman correlation, rho = 0.50, $p < 0.002$) between PTA and SNR50 obtained from the poorer ear. This result shows that the higher (poorer) the PTA threshold in UHL subjects, the lower the ability to discriminate speech in noise. There was a similar negative correlation between speech recognition in quiet and SNR50 (Spearman correlation, rho = 0.72, $p < 0.0001$). This suggests that a deficit in the ability to recognize speech in quiet was reflected in a deficit to recognize speech in noise. We did not observe such a relationship when the PTA versus SNR50 from the better ear were plotted alone (rho = 0.08, p = 0.66) probably due to the lack of range in PTA values.

Secondly, some subjects showed a deficient SNR50 in the reverse dichotic listening situation. This condition, where the signal is presented to the better ear and noise to the contralateral side, should represent the most advantageous listening situation for UHLs. Based on the results observed in this condition for the NHL group tested with a unilateral ear-plug (35 dB attenuation on average, Table 2), a mild deficit to near-to-normal SNR50 were expected for UHLs. However, the UHL group showed a significant deficit in the reverse dichotic condition compared to the NHL group, tested with and without the plug (Table 2, bootstrap $p<0.05$). Moreover, UHL subjects showed highly variable SNR50 scores: from + 1 dB for the poorest score to -12.6 dB for the best one (see figure 1 A). A close inspection of individual data in the reverse dichotic condition revealed that 21 out of 35 UHL subjects had a SNR50 level in the normal range (defined as “Good” performers) but in the remaining 14 UHL subjects (defined as “Bad” performers), the SNR50 level could be considered as deficient (see figure 1 B). Table 2 gives the SNR50 scores in the NHL group, with and without unilateral plug and for the Good and Bad UHL subgroups within each listening condition.

In order to identify the origin of this difference, several factors were explored and compared between the Bad and Good subgroups. Simple demographic factors were first examined and no significant difference was found for age (Good: 46.28 years ±11.82; Bad:  50.35 ±10.90), gender, or side of deafness between the two subgroups. Further the duration of deafness was comparable between both groups (Good: 57.14 months ±119.83; Bad: 57.35 ±83.14).

According to bootstrap 95 % confidence intervals, the Good subgroup had significantly poorer SNR50s than the NHL group for both dichotic and diotic listening conditions while, by definition, no significant difference was found for the reverse dichotic condition (Figure 2). Conversely, subjects of the Bad subgroup showed poorer SNR50s within all listening conditions compared to both the NHL group ($d$ = 4.02 in dichotic, $d$ = 2.62 in diotic, and $d$ = 3.08 in reverse dichotic).and Good group ($d$ = -1.03 in dichotic, $d$ = -1.27 in diotic, and $d$ = -2.33 in reverse dichotic).

PTAs were also investigated but there were no significant differences (bootstrap 95 % confidence intervals) between the two subgroups: Pure-tone air conduction thresholds were similar (figure.3) for the better ear (BE, Good: 10.29 dB ± SD 5.41; Bad: 11.78 dB ±4.20) and for the poorer ear, (PE, Good: 53.51 dB ±23.34; Bad: 59.64 dB ±25.29) leading to similar hearing asymmetries in both groups (Dif, Good: 43.21 dB ±21.91; Bad: 47.85 dB ±25.03).

The comparison was also performed on bone conductions thresholds because several subjects (5 for Bad and 16 for Good) encompassed conductive or mixed hearing loss in the two subgroups. Better ears (Good: 9.04 dB ± SD 4.84; Bad: 9.34 dB ±4.35) and poorer ears (Good: 28.66 dB ± SD 18.97; Bad: 37.97 dB ± 21.33) still presented comparable bone conduction thresholds leading to a similar hearing asymmetry (Good: 43.21 ± SD 21.91; Bad: 47.85 ± 25.03). (All comparisons based on bootstrap 95 % confidence intervals.

Thirdly, speech recognition thresholds (SRT) in quiet were similar between Good and Bad subgroups (figure 3, right). There was large variability in both subgroups and SRTs were not significantly different (according to bootstrap 95 % confidence intervals) either for better ears (Good: 15 dB ±9.48, Bad: 24.28 dB ±16.15) or for poorer ears (Good: 39.28 dB ±27.76; Bad: 48.92 dB ±45.53).

While all the previous comparisons showed that the severity the deafness was comparable between both subgroups, and that no other auditory factors could be identified, it appeared that the main difference could reside in the etiology of the unilateral hearing loss (figure 4). In the Good subgroup, 18 out of 21 subjects (85%) had a middle ear disorder such as otosclerosis or chronic otitis sequelae. In the Bad subgroup, 9 out of 14 subjects (64%) had retrocochlear sensorineural hearing loss with 8 subjects presenting a vestibular schwannoma stage III or IV and one a facial schwannoma stage I. An example of a vestibular schwannoma stage IV is depicted on figure 5. There was a significant effect of the etiology on SNR50 (exact test of Fischer's, p< 0.001). Further, based on a Z-test of proportions for small samples, a vestibular schwannoma stage III or IV leads any one subject to belong to the Bad subgroup with a probability up to 71%. Conversely, a middle ear disorder (such as otosclerosis for instance) was accompanied by a probability up to 59.4% of belonging to the Good subgroup.

In summary, these analyses show that the etiology of the hearing loss would be the main factor that underlies the performance difference between the Good and Bad subgroups in the reverse dichotic condition. The high proportion of compressive vestibular schwannomas in the Bad subgroup suggests that the functional integrity of the lower brainstem is mandatory to obtain normal SNR50s in the reverse dichotic condition.

Further evidence for the role of compression of the brainstem in these processes was made based on changes to SNR50 in a subset of seven subjects followed up after surgical removal of the schwannoma. Before surgery, all seven subjects belonged to the Bad group with a mean SNR50s of -4.34 dB (±2.45) in the reverse dichotic condition. After a post-surgery period of approximately 5 months (range 2-9 months) we evaluated SNR50 for these patients using the French Matrix test and different lists of sentences to avoid learning effects. In this second evaluation we observed that SNR50s were significantly improved in these seven subjects to reach a mean value of -6.95 (± 2.06), which is comparable to that observed in the Good group and within the normal range. Among these seven subjects, in comparison to the preoperative SNR50s, we measured a mean gain of 2.42 dB SNR (±3.09), which corresponds to a 56% improvement of initial performance. Furthermore, no correlation (rho = 0.55, p =

0.19) was found between the SNR gain obtained post-surgery and the post-op duration.

All together, these results provide clear evidence that in cases of UHL the integrity of the brainstem structures contralateral to the better ear is crucial to preserve speech recognition in noise under certain spatial hearing conditions.

## 4. DISCUSSION

This study revealed within a UHL population a significant relationship between a peripheral deficit as documented by the pure-tone audiometry and an integrative auditory function, speech recognition-in-noise. This relationship is affected when the binaural neural structures located in the brainstem are altered. Indeed, when unilateral hearing loss is due to a lesion affecting the pons, such as large vestibular schwannomas, residual binaural integration is more deficient compared to the deficit observed after peripheral hearing loss.

### *4.1 Audiometry and binaural hearing processing*.

The first aim of this study was to determine within a population of subjects with unilateral hearing loss if pure-tone auditory thresholds could provide a reliable prediction of binaural abilities, such as speech recognition in noise. Our results clearly established a relationship between the pure-tone-average hearing threshold and speech recognition thresholds in noise in an adult UHL population, when the signal and the maskers were presented from different spatial positions. The poorer (higher) the hearing thresholds, the poorer the speech recognition in noise. Bronkhorst and Plomp (1989) assessed the relationship between PTA and speech recognition thresholds in quiet, or in the presence of a competing noise, within a population with asymmetric hearing loss. A correlation between the PTA and speech reception thresholds in quiet was found, but not for speech reception thresholds in noise. One reason could be that in their study PTAs were averaged over a restricted set of 3 frequencies (0,5; 1 and 2 kHz), a measure that lacks some of the essential consonant perception around 4 kHz, which can help listeners to segregate speech in the presence of competing noise (Smoorenburg, 1992). In support of this hypothesis, the Smoorenburg study reported a correlation between SRT in noise and the pure tone audiometry values obtained at 4 kHz.

Thus in the specific case of UHL in which hearing in the good ear is within the normal range, the PTA in the poorer ear can be predictive of difficulties in processing speech in noise. In a previous study, but on a limited set of UHL subjects, we have shown that the sound localization ability is also related to the PTA values. Such results have a clinical importance because UHL, or more generally asymmetric hearing loss, impacts strongly on the quality of life, through the impairment of communication in adverse noisy situations (Chisolm et al., 2007; Parving et al., 2001; Vannson et al., 2015). However, one should keep in mind that PTA cannot be the only criterion for assessing auditory deficit. There is now a large set of evidence demonstrating the presence of deficit in auditory processing in spite of normal audiometry especially following noise-exposure (see Plack et al., 2014) or normal aging (Füllgrabe et al., 2013). In the case of hidden hearing loss, the deficits are observed for temporal aspects of sound processing (Kumar et al., 2012) and it would be interesting to test if binaural integration is preserved as expected from the normal PTA in those subjects.

### *4.2 Unilateral hearing loss and binaural processing for speech recognition in noise*.

Binaural hearing was assessed by the FrMatrix test in three listening conditions. Both dichotic and reverse dichotic listening conditions mostly evaluated the passive head-shadow effect and the Squelch effect (spatial release from masking) by spatially separating the target from the masker in order to increase the SNR to each ear of the subject. The diotic listening condition where the target and the masker are co-located assesses the binaural summation or redundancy effect. Globally, UHL present significant higher (i.e. poorer) speech recognition thresholds in noise as measured by SNR50 in all listening situations due to their reduced ability to process binaural ILD and ITD information properly (van Schijndel et al., 2001; Bronkhorst & Plomp, 1989).  More specifically, due to their unbalanced hearing, the UHL group also presented poorer mean SNR50 in the diotic condition in which both signal and masker are co-localized. The diotic condition involves central binaural summation (Avan et al., 2015) as demonstrated by the increased SNR50s found for NHLs with one ear plugged (Table 2) and also found for UHL subjects in numerous studies including the present one (Bronkhorst & Plomp, 1989; Rothpletz et al., 2012). Heil et al. (2014) developed a mathematical model that proposed that the binaural redundancy effect can provide up to 3 dB benefit only in cases where individuals have a strictly symmetric auditory thresholds  (Heil, 2014). Such a hypothesis is supported for NHLs as well as bilateral symmetrical hearing loss subjects (Hawkins et al.,1987).  Our UHL subjects had better-ear PTAs <20 dB HL (in the normal range) and thus we expected to find a significant correlation between the diotic SNR50 and the PTA asymmetry (defined as the difference between the better ear PTA and the poorer ear PTA). However, no relationship was found between these two variables implying that a central factor in addition to hearing thresholds may account for the binaural summation effect.

When the speech signal and the competing noise are spatially separated, i.e in dichotic and in reverse dichotic conditions, UHL subjects presented strong deficits. These deficits illustrate the difficulty for UHL subjects to segregate speech from noise in conditions which rely on binaural processing by combining both the benefit from the head shadow as well as from binaural squelch (Avan et al., 2015). Again our data are in agreement with similar studies to the present one within an adult population (Rothpletz et al., 2012; Firszt et al., 2015) or even within an pediatric population (Reeder et al, 2015; Ruscetta et al., 2005) However when looking more closely at individual data we were able to separate UHL subjects into two subgroups according to their ability to recognize speech in the reverse dichotic condition (by definition, see the result section): However these two subgroups also showed significantly different performance in the dichotic listening condition (Figure 2, left).

Speech recognition in noise improves in NHLs when the noise is spatially separated from the speech by increasing the SNR due to the passive head-shadow effect (Peissig & Kollmeier, 1997; Colburn et al., 2006). In the reverse dichotic listening condition, UHL subjects of the Bad subgroup maintained the physical benefit of the head-shadow effect, which preserved the advantageous signal-to-noise ratio in this condition where the speech was presented to the better ear. Though poorer than the NHL group and Good subgroup, the average SNR50 of -4.31 dB therefore corresponds closely to the passive benefit provided by the head-shadow (see Zurek, 1993). The loss of squelch effect (spatial unmasking) is likely responsible for the Bad subgroup's deficit in this condition, and probably underpins the poorer mean SNR50 showed in the dichotic condition (-0.85 dB in Bad versus -3.16 dB in Good). Indeed and as demonstrated above, the relative resistance of spatial unmasking in Good compared to Bad cannot be attributed to hearing thresholds (for pure-tones as for speech recognition in quiet). The performance gap between subgroups might be explained by differences in the adaptation to monaural hearing (Bronkhorst, 2000).

### *4.3 A putative role of the brainstem in monaural adaptation*

The distinction between Bad and Good subgroups was based on individual values of SNR50 without any indication of the origins that could account for this difference for speech recognition in noise. Both subgroups presented the same level of hearing loss as assessed using the classical pure-tone audiometry (see figure 3) (both air and bone conduction) and speech recognition in quiet, and all the other audiological features failed to reveal differences. The only distinction between Good and Bad subgroups appeared to be the distribution of the etiologies of deafness (figure 4) and such differences could support the differences in auditory processing ability.

Firstly, most of the Good (18 out of 21) displayed an acquired conductive hearing loss. One could speculate that their ability to segregate speech and noise in the reverse dichotic condition might come from the fact that a large amount of energy can bypass the external and middle ear to reach the inner ear by bone or skull vibrations (Noble et al., 1997). In our experiment, the speech level was fixed at 65 dB SPL, which is greater than the average transcranial attenuation of 50 dB that would enable some of the target speech energy to reach the contralateral better inner ear by bone conduction in the dichotic listening condition Lastly, we did not observe any correlation between bone conduction thresholds and SNR50 (rho = 0.34, p = 0.15) adding further evidence that bone conduction was not substantially involved. To conclude, while such mechanisms could account for some improved performance in both groups, the implication of bone conduction cannot fully account for the higher ability of Good subgroup compared to the Bad subgroup in the dichotic condition.

One hypothesis is that the Good subgroup subjects have been able to develop adaptive capacities to process monaural information, a skill that was not operating in the majority of the Bad subgroup subjects because of their retrocochlear disorder due to a stage III-IV vestibular schwannoma (VS). According to the size of the tumor (Koos & Speltzer, 1976), a VS can expand towards the lower brainstem structures leading to hearing disorders or auditory distortions and a lower quality of life (Douglas et al., 2007; Tatagiba & Acioly, 2014). Stage III is defined as being close to the brainstem structures without causing compression while auditory distortions can occur probably due compression of the artery system around the brainstem (Tatagiba & Acioly, 2014). Stage IV corresponds to a tumor greater than 30 mm in size that effectively compresses the brainstem structures up to the fourth ventricle as in patient S31 illustrated in figure 5. We hypothesize that in these cases the VS affects the Ventral Cochlear Nucleus (VCN) and the Dorsal Cochlear Nucleus (DCN), which are important for spectral and directional information processing, leading to lower performance in the reverse dichotic condition where the speech signal was presented towards the better ear.

The VCN receives input from auditory neurons from both ears and is known as the lowest auditory relay stage for binaural integration. Conversely the DCN receives monaural information and thus constitutes a crucial relay to process directional spectral cues provided by the head-related transfer function (HRTF), which are critical for sound source localization in the vertical dimension (Middlebrooks & Green, 1991). However, the DCN also receives contralateral inputs (Cant & Gaston, 1982; Schofield & Cant, 1996; Shore et al., 1992) providing additional information from the opposite ear (see Imig et al., 2000). It has been proposed that these commissural inputs would participate in the enhancement of spectral processing performed in the DCN (Davis, 2005).

Based on the functional properties of the brainstem nuclei it is possible that the compression of the brainstem nuclei by a VS stage IV would affect either the residual capacity to process binaural information or the capacity to develop adaptive abilities to use monaural spectral information. While the brainstem is involved in ITD/ILD integration (Furst et al., 2000; Furst & Algom, 1995; Levine et al., 1993), the fact that after surgical removal of the VS those patients' improved their performance in the reverse dichotic condition - to reach that observed in the Good subgroup – suggests mainly the monaural hypothesis. Based on these etiological differences, we suggest that the integrity of the brainstem, including the DCN, would allow UHL patients to process at a higher level monaural spectral cues that are important during speech recognition in noisy environments. Spectral processing can be positively improved through perceptual learning mechanisms (Irvine & Wright, 2005) and some studies have revealed near-normal performance for certain UHL patients for some sound localization tasks (Häusler et al.,1983 ; Slattery & Middlebrooks, 1994). As described in the methods, we took care to exclude the possibility of task-learning effects using unpredictable sentences. This suggests that the observed improvement is due to central plasticity mechanisms after the deleterious functional impact of the vestibular schwannoma on brainstem monaural processing has been eliminated. Further our results tend to suggest that the functional plasticity that allows UHL patients to reach near-normal values in the reverse dichotic condition is a relatively fast process. Indeed, it seems that the recuperation is not a slowly progressive mechanism because no correlation was found between the duration post-surgery and speech recognition thresholds in noise. However, the limited sample of patients prevents a strong stance on the dynamic of functional recovery. From a theoretical point of view, the present study highlights the possible role of the brainstem in the acquisition of enhanced skills to process monaural spectral information and as a crucial integrator for speech recognition in noise.

## 5. CONCLUSION

This study has important applications both at clinical and theoretical levels with respect to the processing of speech in noise. First it reveals that pure-tone audiometry can be used in some patients with unilateral hearing loss as a good predictor of deficits in speech recognition in noise. Second, the compensatory monaural spatial release from masking of the better ear can be affected by the loss of functional integrity of the brainstem. Indeed the compression of the DCN by a vestibular schwannoma may disrupt such ability through alteration of the development of adaptive mechanisms of processing monaural spectral directional cues. Altogether, in agreement with animal models, our results present original evidence in humans of the role of the brainstem nuclei in monaural spectral processing which are important for understanding speech in noise.

### Disclosure Statement

Nicolas Vannson and Chris James are employees of Cochlear France SAS.

### Acknowledgements

This study was support by a Cifre Convention to NV (Cochlear France – ANRT N°1463/2012), the recurrent funding of the CNRS, the AOL DRCI CHU Purpan (N° 2014-A00498-39) to OD and MM, and the ANR VirtualHearing3D to PB, OD and MM.

# References

Avan, P., Giraudet, F., & Buki, B. (2015). Importance of Binaural Hearing. *Audiol Neurootol, 20 Suppl 1*, 3-6. doi: 10.1159/000380741

Bilecen, D., Seifritz, E., Radü, E., Schmid, N., Wetzel, S., Probst, R., & Scheffler, K. (2000). Cortical reorganization after acute unilateral hearing loss traced by fMRI. *Neurology, 54*(3), 765-765.

Bronkhorst, A. W. (2000). The cocktail party phenomenon: A review of research on speech intelligibility in multiple-talker conditions. *Acta Acustica united with Acustica, 86*(1), 117-128.

Bronkhorst, A. W., & Plomp, R. (1989). Binaural speech intelligibility in noise for hearing-impaired listeners. *J Acoust Soc Am, 86*(4), 1374-1383.

Cant, N. B., & Gaston, K. C. (1982). Pathways connecting the right and left cochlear nuclei. *Journal of Comparative Neurology, 212*(3), 313-326.

Carpenter, J., & Bithell, J. (2000). Bootstrap confidence intervals: when, which, what? A practical guide for medical statisticians. *Stat Med, 19*(9), 1141-1164.

Cherry, E. C. (1953). Some experiments on the recognition of speech, with one and with two ears. *J Acoust Soc Am, 25*(5), 975-979.

Ching et al. Binaural Benefits for Adults Who Use Hearing Aids and Cochlear Implants in Opposite Ears. *Ear Hear*. 2004; 25 (1):9-21

Chisolm, T. H., Johnson, C. E., Danhauer, J. L., Portz, L. J., Abrams, H. B., Lesner, S., . . . Newman, C. W. (2007). A systematic review of health-related quality of life and hearing aids: final report of the American Academy of Audiology Task Force On the Health-Related Quality of Life Benefits of Amplification in Adults. *J Am Acad Audiol, 18*(2), 151-183.

Davis, K. A. (2005). Contralateral effects and binaural interactions in dorsal cochlear nucleus. *Journal of the Association for Research in Otolaryngology, 6*(3), 280-296.

Douglas, S. A., Yeung, P., Daudia, A., Gatehouse, S., & O'Donoghue, G. M. (2007). Spatial hearing disability after acoustic neuroma removal. *Laryngoscope, 117*(9), 1648-1651.

Durlach NJ, Colburn HS (1978). Binaural Phenomena: handbook of perception. San Diego, Academic Press, p. 373-406

Firszt, J. B., Reeder, R. M., Dwyer, N. Y., Burton, H., & Holden, L. K. (2015). Localization training results in individuals with unilateral severe to profound hearing loss. *Hear Res, 319*, 48-55. doi: 10.1016/j.heares.2014.11.005

Füllgrabe, C., Moore, B. C., & Stone, M. A. (2013). Age-group differences in speech identification despite matched audiometrically normal hearing: contributions from auditory temporal processing and cognition. *Frontiers in aging neuroscience, 6*.

Furst, M., Aharonson, V., Levine, R. A., Fullerton, B. C., Tadmor, R., Pratt, H., . . . Korczyn, A. D. (2000). Sound lateralization and interaural discrimination. Effects of brainstem infarcts and multiple sclerosis lesions. *Hear Res, 143*(1-2), 29-42.

Furst, M., & Algom, D. (1995). Lateralization and discrimination of dichotic clicks: evidence from patients with brainstem lesions and normal cohorts. *J Basic Clin Physiol Pharmacol, 6*(2), 149-171.

Giolas, T. G., & Wark, D. J. (1967). Communication problems associated with unilateral hearing loss. *J Speech Hear Disord, 32*(4), 336-343.

Grothe, B., Pecka, M., & McAlpine, D. (2010). Mechanisms of sound localization in mammals. *Physiol Rev, 90*(3), 983-1012. doi: 10.1152/physrev.00026.2009

Häusler, R., Colburn, S., & Marr, E. (1983). Sound localization in subjects with impaired hearing: spatial-discrimination and interaural-discrimination tests. *Acta Oto-Laryngologica, 96*(sup400), 1-62.

Hawkins, D. B., Prosek, R. A., Walden, B. E., & Montgomery, A. A. (1987). Binaural loudness summation in the hearing impaired. *Journal of Speech, Language, and Hearing Research, 30*(1), 37-43.

Heil, P. (2014). Towards a unifying basis of auditory thresholds: binaural summation. *Journal of the Association for Research in Otolaryngology : JARO, 15*(2), 219-234. doi: 10.1007/s10162-013-0432-x

Imig, T. J., Bibikov, N. G., Poirier, P., & Samson, F. K. (2000). Directionality derived from pinna-cue spectral notches in cat dorsal cochlear nucleus. *Journal of neurophysiology, 83*(2), 907-925.

Irvine, D., & Wright, B. (2005). Plasticity of spectral processing.

Jansen, S., Luts, H., Wagener, K. C., Kollmeier, B., Del Rio, M., Dauman, R., . . . van Wieringen, A. (2012). Comparison of three types of French speech-in-noise tests: a multi-center study. *Int J Audiol, 51*(3), 164-173.

Killion, M. C., & Niquette, P. A. (2000). What can the pure-tone audiogram tell us about a patient's SNR loss ? *Hear J, 53*(3), 46-53.

Koos, W., & Speltzer, R. (1976). Microsurgery of cerebellopontine angle tumors, in clinical microneurosurgery: Stutgart.

Kral, A. (2013). Auditory critical periods: a review from system's perspective. *Neuroscience, 247*, 117-133.

Kral, A., Heid, S., Hubka, P., & Tillein, J. (2013). Unilateral hearing during development: hemispheric specificity in plastic reorganizations. *Frontiers in systems neuroscience, 7*.

Kumar, U. A., Ameenudin, S., & Sangamanatha, A. (2012). Temporal and speech processing skills in normal hearing individuals exposed to occupational noise. *Noise and Health, 14*(58), 100.

Langers, D. R. M., van Dijk, P., & Backes, W. H. (2005). Lateralization, connectivity and plasticity in the human central auditory system. *Neuroimage, 28*(2), 490-499.

Levine, R. A., Gardner, J. C., Fullerton, B. C., Stufflebeam, S. M., Carlisle, E. W., Furst, M., . . . Kiang, N. Y. (1993). Effects of multiple sclerosis brainstem lesions on sound lateralization and brainstem auditory evoked potentials. *Hear Res, 68*(1), 73-88.

Levitt H, Rabiner LR (1967) jasa

Litovsky, R. Y., Fligor, B. J., & Tramo, M. J. (2002). Functional role of the human inferior colliculus in binaural hearing. *Hear Res, 165*(1-2), 177-188.

Maslin, M. R., Taylor, M., Plack, C. J., & Munro, K. J. (2015). Enhanced intensity discrimination in the intact ear of adults with unilateral deafness. *J Acoust Soc Am, 137*(6), EL408-414. doi: 10.1121/1.4914945

McAlpine, D., Martin, R. L., Mossop, J. E., & Moore, D. R. (1997). Response properties of neurons in the inferior colliculus of the monaurally deafened ferret to acoustic stimulation of the intact ear. *J Neurophysiol, 78*(2), 767-779.

Middlebrooks, J. C., & Green, D. M. (1991). Sound localization by human listeners. *Annual review of psychology, 42*(1), 135-159.

Moore, D. R. (1991). Anatomy and physiology of binaural hearing. *Audiology, 30*(3), 125-134.

Moore, D. R. (1994). Auditory brainstem of the ferret: long survival following cochlear removal progressively changes projections from the cochlear nucleus to the inferior colliculus. *J Comp Neurol, 339*(2), 301-310. doi: 10.1002/cne.903390209

Moore, D. R., & King, A. J. (2004). Plasticity of binaural systems *Plasticity of the Auditory System* (pp. 96-172): Springer.

Munro, K. J. (2008). Reorganization of the adult auditory system: perceptual and physiological evidence from monaural fitting of hearing aids. *Trends Amplif, 12*(3), 254-271. doi: 10.1177/1084713808323483

Noble, W., Byrne, D., & Ter-Horst, K. (1997). Auditory localization, detection of spatial separateness, and speech hearing in noise by hearing impaired listeners. *J Acoust Soc Am, 102*(4), 2343-2352.

Parving, A., Parving, I., Erlendsson, A., & Christensen, B. (2001). Some experiences with hearing disability/handicap and quality of life measures. *Audiology, 40*(4), 208-214.

Peissig, J., & Kollmeier, B. (1997). Directivity of binaural noise reduction in spatial multiple noise-source arrangements for normal and impaired listeners. *J Acoust Soc Am, 101*(3), 1660-1670.

Perrett, S., & Noble, W. (1995). Available response choices affect localization of sound. *Perception & psychophysics*, *57*(2), 150-158.

Plack, C. J., Barker, D., & Prendergast, G. (2014). Perceptual consequences of "hidden" hearing loss. *Trends in hearing, 18*, 2331216514550621.

Ponton, C. W., Vasama, J. P., Tremblay, K., Khosla, D., Kwong, B., & Don, M. (2001). Plasticity in the adult human central auditory system: evidence from late-onset profound unilateral deafness. *Hear Res, 154*(1-2), 32-44.

Popelar, J., Erre, J. P., Aran, J. M., & Cazals, Y. (1994). Plastic changes in ipsi-contralateral differences of auditory cortex and inferior colliculus evoked potentials after injury to one ear in the adult guinea pig. *Hear Res, 72*(1-2), 125-134.

Rothpletz, A. M., Wightman, F. L., & Kistler, D. J. (2012). Informational masking and spatial hearing in listeners with and without unilateral hearing loss. *J Speech Lang Hear Res, 55*(2), 511-531. doi: 10.1044/1092-4388(2011/10-0205)

Scheffler, K., Bilecen, D., Schmid, N., Tschopp, K., & Seelig, J. (1998). Auditory cortical responses in hearing subjects and unilateral deaf patients as detected by functional magnetic resonance imaging. *Cereb Cortex, 8*(2), 156-163.

Schofield, B. R., & Cant, N. B. (1996). Origins and targets of commissural connections between the cochlear nuclei in guinea pigs. *Journal of Comparative Neurology, 375*(1), 128-146.

Shore, S. E., Godfrey, D. A., Helfert, R. H., Altschuler, R. A., & Bledsoe, S. C. (1992). Connections between the cochlear nuclei in guinea pig. *Hearing research, 62*(1), 16-26.

Slattery, W. H., 3rd, & Middlebrooks, J. C. (1994). Monaural sound localization: acute versus chronic unilateral impairment. *Hear Res, 75*(1-2), 38-46.

Smoorenburg, G. F. (1992). Speech reception in quiet and in noisy conditions by individuals with noise-induced hearing loss in relation to their tone audiogram. *J Acoust Soc Am, 91*(1), 421-437.

Steven Colburn, H., Shinn-Cunningham, B., Kidd, G., Jr., & Durlach, N. (2006). The perceptual consequences of binaural hearing. *Int J Audiol, 45 Suppl 1*, S34-44.

Syka, J. (2002). Plastic changes in the central auditory system after hearing loss, restoration of function, and during learning. *Physiol Rev, 82*(3), 601-636. doi: 10.1152/physrev.00002.2002

Tatagiba, M., & Acioly, M. A. (2014). Vestibular Schwannoma: current state of the art *Samii's Essentials in Neurosurgery* (pp. 265-283): Springer.

van Schijndel, N. H., Houtgast, T., & Festen, J. M. (2001). The effect of intensity perturbations on speech intelligibility for normal-hearing and hearing-impaired listeners. *J Acoust Soc Am, 109*(5 Pt 1), 2202-2210.

Van Wanrooij, M. M., & Van Opstal, A. J. (2004). Contribution of Head Shadow and Pinna Cues to Chronic Monaural Sound Localization. *J Neurosci, 24*(17), 4163-4417.

Vannson, N., James, C., Fraysse, B., Strelnikov, K., Barone, P., Deguine, O., & Marx, M. (2015). Quality of Life and Auditory Performance in Adults with Asymmetric Hearing Loss. *Audiol Neurootol, 20 Suppl 1*, 38-43. doi: 10.1159/000380746

Vasama, J.-P., Mäkelä, J. P., Pyykkö, I., & Hari, R. (1995). Abrupt unilateral deafness modifies function of human auditory pathways. *Neuroreport, 6*(7), 961-964.

Zurek, P. M. (1993). Binaural advantages and directional effects in speech intelligibility. *Acoustical factors affecting hearing aid performance, 2*, 255-275.

**Table 1: Cohort population: Patients and controls information.** R and L stand for right and left ear respectively. PTA means pure-tone average which is the average of 500, 1000, 2000 and 4000 Hz.

| Subject number | gender | Age (years) | etiology | Hearing loss side | duration of deafness (months) | Better ear PTA | Poorer ear PTA |
|---|---|---|---|---|---|---|---|
| 1 | F | 54 | Vestibular schwannoma (VS) stage IV | R | 2 | 11,25 | 62,5 |
| 2 | F | 43 | VS stage IV | R | 3 | 17,5 | 28,75 |
| 3 | F | 46 | Otosclerosis | L | 2 | 13,75 | 61,25 |
| 4 | F | 47 | Otosclerosis | R | 32 | 13,75 | 42,5 |
| 5 | M | 31 | Chronic otitis sequelae | R | 3 | 1,25 | 26,25 |
| 6 | M | 52 | Otosclerosis | R | 450 | 7,5 | 66,25 |
| 7 | M | 35 | VS stage III | L | 2 | 10 | 40 |
| 8 | M | 46 | VS stage IV | L | 10 | 17,5 | 120 |
| 9 | F | 57 | Otosclerosis | L | 136 | 17,5 | 61,25 |
| 10 | M | 45 | VS stage IV | L | 3 | 5 | 35 |
| 11 | M | 54 | Chronic otitis sequelae | R | 300 | 12,5 | 37,5 |
| 12 | M | 51 | Chronic otitis sequelae | R | 20 | 13,75 | 52,5 |
| 13 | M | 65 | Otosclerosis | L | 0 | 18,75 | 53,75 |
| 14 | F | 67 | Facial nerve schwannoma stage I | L | 12 | 15 | 76,25 |
| 15 | M | 41 | VS stage II | L | 4 | 7,5 | 37,5 |
| 16 | F | 55 | VS stage IV | R | 28 | 8,75 | 55 |
| 17 | F | 65 | Otosclerosis | R | 2 | 10 | 37,5 |
| 18 | M | 34 | Otosclerosis | L | 53 | 10 | 43,75 |
| 19 | F | 52 | Chronic otitis sequelae | L | 4 | 6,25 | 51,25 |
| 20 | F | 41 | Otosclerosis | L | 3 | 17,5 | 43,75 |
| 21 | F | 62 | Otosclerosis | R | 63 | 5 | 52,5 |
| 22 | F | 53 | Otosclerosis | R | 1 | 16,25 | 46,25 |
| 23 | F | 61 | Otosclerosis | L | 3 | 12,5 | 36,25 |
| 24 | M | 58 | Chronic otitis sequelae | L | 129 | 10 | 53,75 |
| 25 | M | 62 | Sudden hearing loss | R | 235 | 18,75 | 87,5 |
| 26 | F | 25 | VS stage IV | L | 67 | 5 | 87,5 |
| 27 | M | 48 | VS stage IV | L | 3 | 8,75 | 32,5 |
| 28 | M | 59 | Chronic otitis sequelae | R | 0 | 3,75 | 66,25 |
| 29 | M | 35 | Cophosis | R | 380 | 1,25 | 120 |
| 30 | F | 40 | Otosclerosis | L | 7 | 8,75 | 35 |
| 31 | M | 54 | VS stage IV | L | 16 | 12,5 | 85 |
| 32 | F | 28 | Otosclerosis | L | 12 | 8,75 | 48,75 |
| 33 | F | 28 | Otosclerosis | L | 5 | 8,75 | 58,75 |
| 34 | F | 44 | VS stage II | R | 7 | 17,5 | 75 |
| 35 | F | 39 | Otosclerosis | R | 6 | 8,75 | 41,25 |
| Mean NHL |  | 40 |  |  |  | 7 | 8 |

Note: The duration of deafness is the time difference between the diagnostic time and the speech recognition evaluation time.

**Table 2: Speech recognition thresholds in noise (SNR50) for normal hearing and UHL subjects for three listening conditions.** UHL subjects were further divided into “Good” and “Bad” performers, where Bad performed significantly worse than NHLs in the reverse dichotic condition. The asterisks show significant differences (p<0.05) between groups based on bootstrap confidence intervals. NS – not significant.

| | | LISTENING CONDITIONS | | |
|---|---|---|---|---|
| | | Dichotic | Diotic | Reverse dichotic |
| SNR50 dB | NHL ears open (n = 11) | -9.59 (SD = 1.53) | -4.98 (SD = 0.78) | -9.59 (SD = 1.53) |
| | NHL ear-plug (n = 11) | -4.42 (SD = 3.08) | -4.37(SD = 1.14) | -9.13 (SD = 1.51) |
| | All UHL (n = 35) | -1.04 (SD = 3.75) | -2.24 (SD = 2.16) | -6.98 (SD = 2.94) |
| | Mean difference (NHL - UHL) | 8.55* | 2.74* | 2.61* |
| | Good (= 21) | -3.16 (SD = 1.72) | -2.44 (SD = 3.46) | -8.77 (SD = 1.86) |
| | Mean difference (NHL - Good) | 6.43 * | 2.54 * | 0.82 *N.S* |
| | Bad (n = 14) | -0.85 (SD = 2.06) | 1.00 (SD = 3.29) | -4.31 (SD = 2.09) |
| | Mean difference (NHL - Bad) | 8.74 * | 3.98 * | 5.28 * |
| | Mean difference (Good - Bad) | 2.31 * | 1.44 * | 4.46 * |

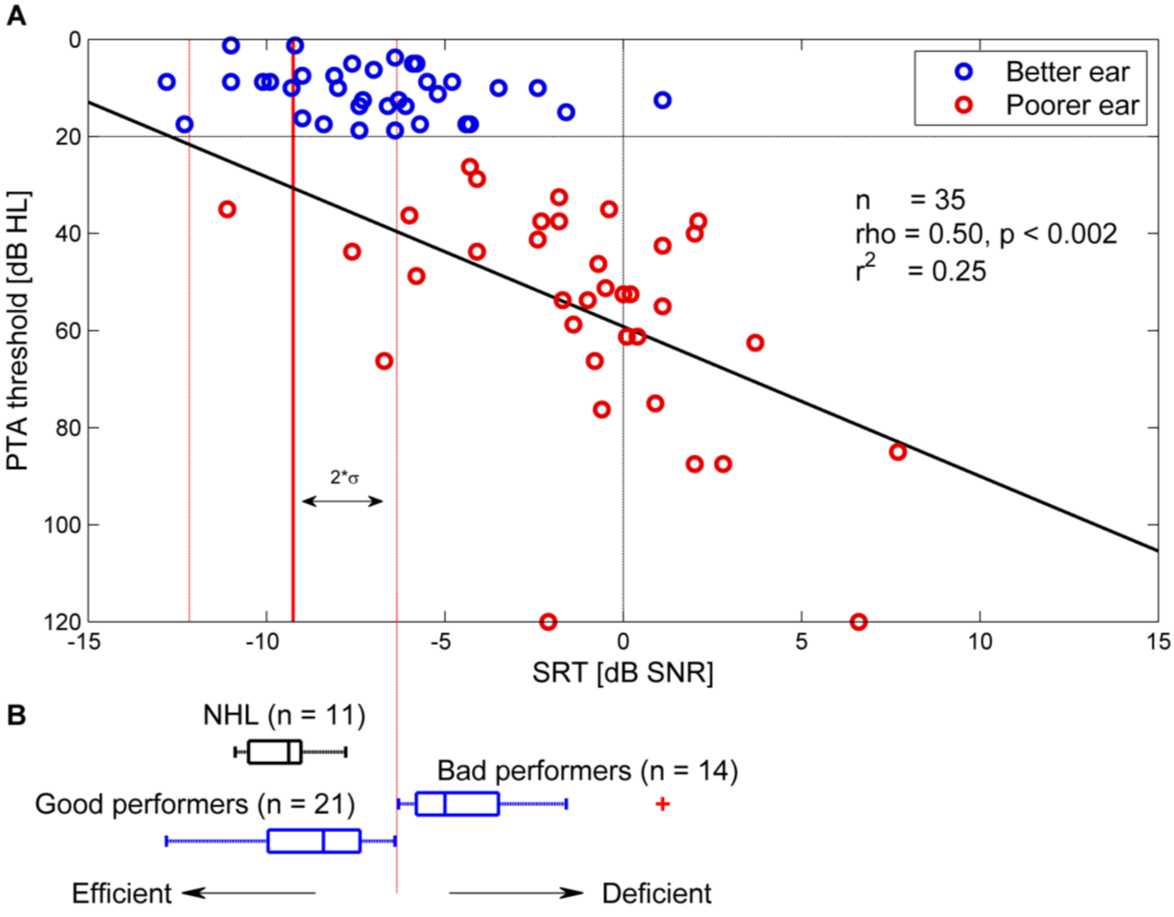

**Figure 1: A) upper. Pure-tone average threshold dB HL (PTA) plotted against SNR50 for UHL subjects.** Levels for better and poorer ears are represented by blue and red circles respectively. Each subject has two points: the better ear PTA is plotted against the reverse dichotic SNR50 and the poorer ear PTA against the dichotic SNR50. The vertical red lines represent the mean SNR50 (bold) and ±2 standard deviations for NHLs. The horizontal black dashed line represents the normal hearing threshold limit (between 0 and 20 dB HL). **B) Lower boxplots represent the SNR50s for the reverse dichotic condition** for the NHL group (black) and the two UHL subgroups for the reverse dichotic condition.

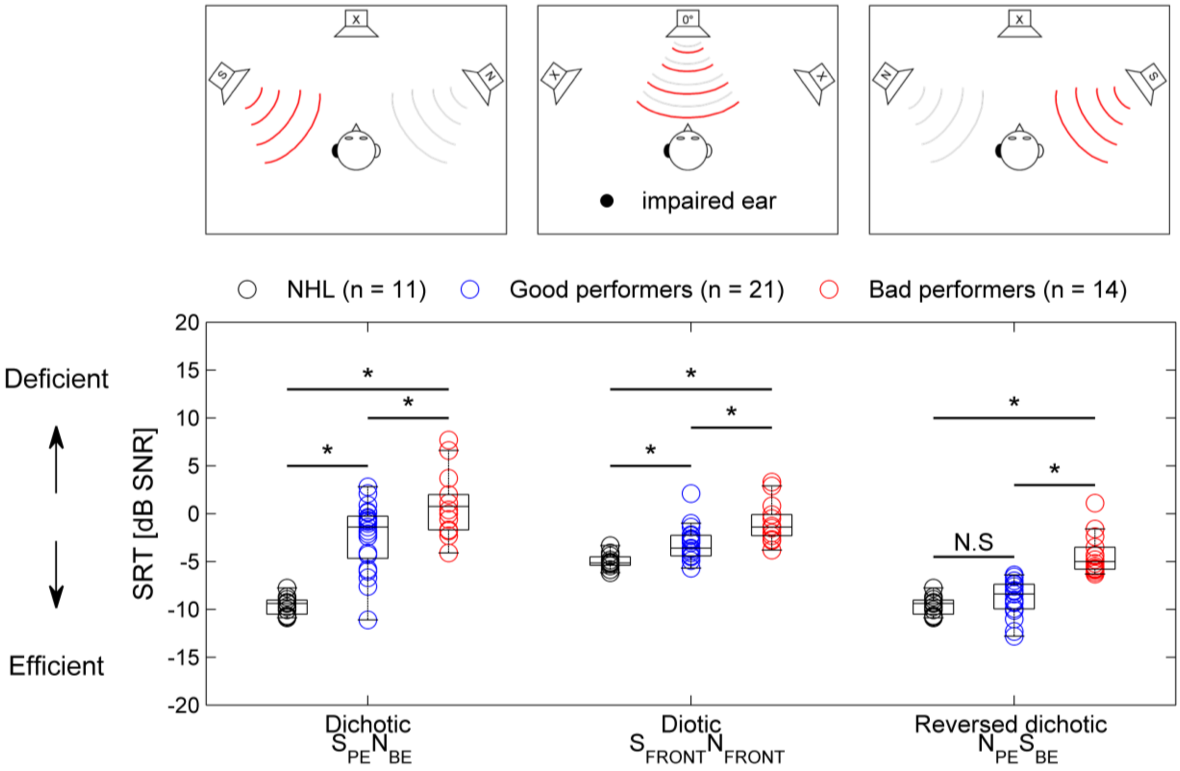

**Figure 2: Speech recognition thresholds in noise for normal hearing and UHL subjects for three listening conditions.** UHL were further divided into “Good” and bad “Bad” performers based on their SNR50 in the reverse dichotic condition (see text). The asterisks show significant differences (p<0.05) between groups based on bootstrap confidence intervals. NS – not significant

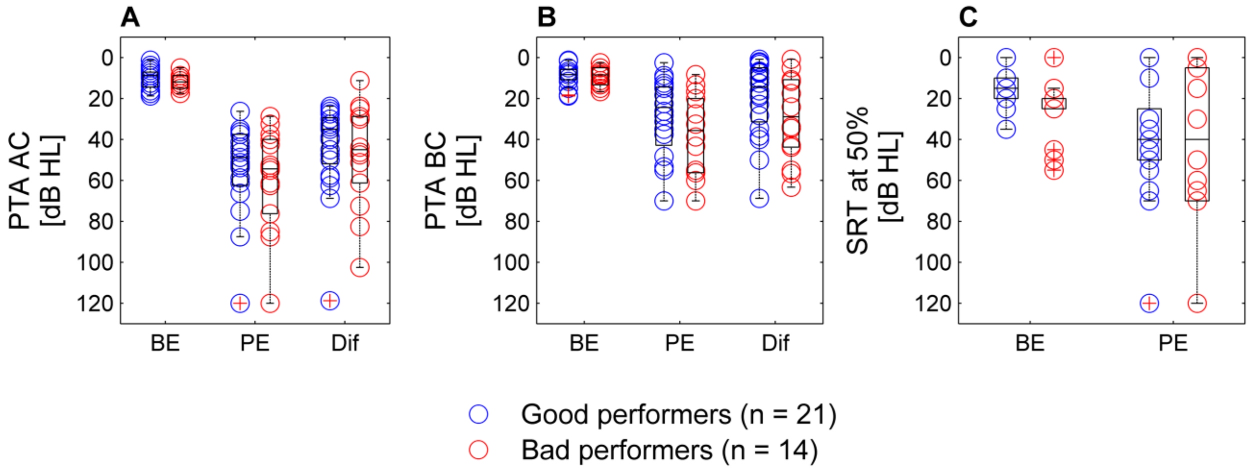

**Figure 3: Good and Bad UHL subgroups compared**. A: Air conduction (AC) PTA thresholds. B: Bone conduction (BC) PTA thresholds. C: Speech reception threshold in quiet (SRT) for 50% correct. BE, PE and dif stand for better ear, poorer ear and difference between the BE and PE. Lines are medians, box limits 25/75 percentiles and error bars confidence limits. Good and Bad subgroups were not significantly different (bootstrap 95 % confident interval).

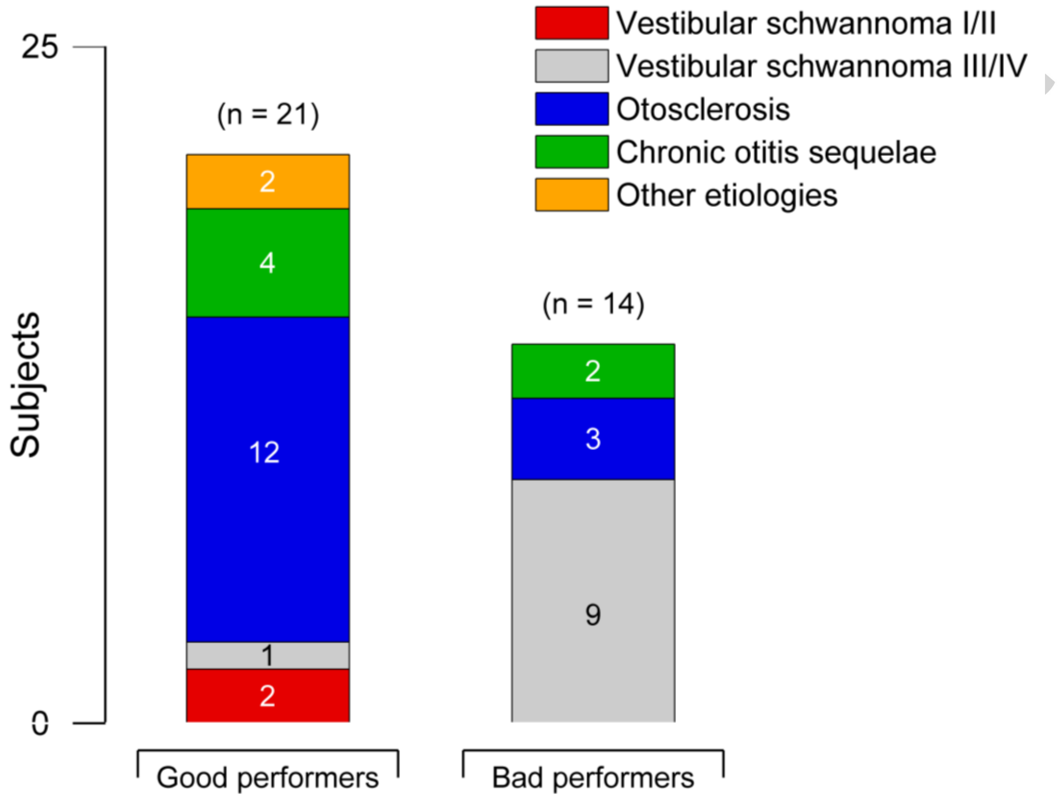

**Figure 4: Etiologies for each UHL group**. The “Other” etiologies category within the Good included a progressive and a sudden hearing loss of unknown origin.

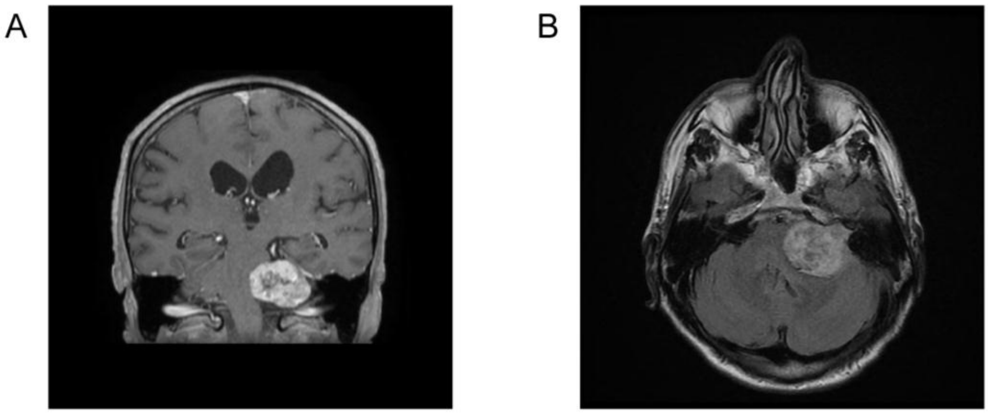

**Figure 5:** **MRI** frontal and axial views from one UHL subject in the Bad subgroup presenting a vestibular schwannoma stage IV.

# Highlights

- Subjects with mild to total unilateral hearing loss were evaluated with both the Matrix test and the clinical routine audiometries.
- Pure-tone air conduction can be a reliable predictor for binaural hearing evaluation.
- Vestibular schwannoma stage III or IV is likely to affect the lower brainstem structure and creates binaural hearing distortions.
- A surgical schwannoma removal may allowed monaural spectral remapping.