■ ORIGINAL ARTICLES

The Effect of Cochlear Sensorineural Hearing Loss on Binaural Integration Mechanisms

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Introduction: Binaural integration is the ability to process different messages when presented simultaneously in both ears. Any deficit in this mechanism implies poor auditory discrimination of background noise and difficulties in processing competing auditory signals.
Method: In the present study, pairs of digits were presented dichotically to both ears in adult subjects with normal hearing and bilaterally symmetrical sensorineural cochlear hearing loss.
Results: Hearing sensitivity, the difficulty in hearing the pairs and the effect of aging determine the capacity for correct recognition. In general, subjects with normal hearing score higher than those with hearing loss. Hypoacusic subjects show a deficit in the recognition of digits presented to the left ear and a greater advantage in the right ear.
Conclusions: The study of binaural integration mechanisms may be useful in the audiological evaluation of patients who reject bilateral amplification and in normal hearing subjects presenting difficulties to understand speech in noisy settings.

Key words: Dichotic digits. Cochlear hearing loss. Aging. Central auditory processing. Binaural integration.

Efecto de la hipoacusia neurosensorial coclear en los mecanismos de integración biauricular
Introducción: La integración biauricular es la habilidad para procesar de forma simultánea por ambos oídos señales acústicas diferentes. El déficit en este mecanismo conlleva una pobre discriminación auditiva en presencia de ruido de fondo y dificultades en el procesamiento de señales acústicas competitivas.
Material y método: En esta investigación se han presentado pares de dígitos de forma dicótica con distintos niveles de dificultad. Los sujetos participantes en este estudio eran adultos con audición normal y con pérdidas auditivas neurosensoriales bilaterales simétricas de origen coclear.
Resultados: El estado auditivo, la dificultad de los ítems y el efecto del envejecimiento determinaron las capacidades de acierto. En general los sujetos normoyentes obtienen mejores puntuaciones que los sujetos con pérdida auditiva. Los sujetos hipoacúsicos muestran un déficit en el reconocimiento de los dígitos presentados por el oído izquierdo y una mayor ventaja del oído derecho.
Conclusiones: El estudio de los mecanismos de integración biauricular puede tener interés en la evaluación audiológica de los pacientes que rechazan la amplificación biauricular y en sujetos que experimentan dificultades en la comprensión del habla en entornos ruidosos con una sensibilidad auditiva normal.

Palabras clave: Escucha dicótica. Hipoacusia coclear. Envejecimiento. Procesamiento auditivo central. Integración biauricular.

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INTRODUCTION

Central auditory processing (CAP) refers to the efficiency and effectiveness by which the central nervous system (CNS) processes auditory information. CAP generates the perception of auditory information, the underlying neurobiological activity, and the physiological responses observed through provoked auditory potentials.[1] The causal mechanisms of CAP are: the localization and lateralization of sound, auditory discrimination, recognition of auditory patterns, and integration by time of competing or degraded acoustic signals.[2-4] CAP disorders (CAPD) are the result of a deficit in the processing of auditory information that affects hearing, speech comprehension, and learning.[5] These deficits are the product of the inability or lack of ability to pay attention, discriminate, recognize, or comprehend auditory information.[6]

The processing of competing acoustic signals depends on the processes of interhemispheric binaural integration. Disorders of this mechanism have been found in patients experiencing hearing difficulties with background noise and normal auditory sensitivity,[7,8] in hearing-impaired patients with hearing aids who reject binaural amplification,[9,10] in children with dyslexia[1] and/or learning disabilities,[12] in patients with lesions of the temporal lobes,[13] in interhemispheric lesions,[14,15] and brainstem lesions.[13,16,17]

The mechanisms of binaural integration can be evaluated by means of dichotic listening (DL) tests such as the dichotic digits test (DDT) or electrophysiological techniques such as the binaural integration component of the auditory brainstem provoked potentials.[18-23] DL testing was described for the first time by Broadbent[24] and subsequently developed by Kimura.[25,26] DL consists of binaural, simultaneous presentation of different acoustic stimuli.[27,28] In normal-hearing, right-handed subjects and in most left-handed subjects with left hemisphere dominance for language processing, better scores are observed in the right ear.[25,26,29,30] This hemispheric dominance is known as right ear advantage (REA) and indicates a positive laterality index (LI). REA is associated with a greater central representation of the contralateral auditory pathways over the ipsilateral ones in the transmission of auditory information. Verbal stimuli presented by the right ear have direct access to the areas that process language in the left hemisphere; whereas those presented by the left ear must travel through the corpus callosum in order to be linguistically processed.[31]

In DL testing, age, auditory sensitivity, and difficulty determine the ability to answer correctly. Aging entails a diminished ability to recognize the items and greater REA.[32-34] The more difficult the test, the greater the REA.[35-37]

In the tests using digits, difficulty is determined by the number of pairs. In tests with 1 or 2 pairs, most neurologically healthy subjects get 100% correct answers, even with an auditory defect.[36,38,39] Several studies with hearing-impaired subjects have revealed that hearing loss does not affect general scores.[13,36,39-43] This resistance to cochlear hearing loss accounts for its use as a CAPD screening procedure. However, there are some differences in the pattern of response in comparison with subjects with normal hearing.[41,42,44] Ling[41] proved that the mechanisms of binaural integration in children with severe sensorineural hearing loss were obliterated. It was thought that in all likelihood, the dominance of the left hemisphere in processing verbal stimuli entailed suppression of the processing of auditory information by the ipsilateral ear. Roeser et al,[42] in a later study with adult hearing-impaired patients, established lower correct answer scores by the left ear as hearing loss increased. The authors concluded that the abolition in the mechanisms of binaural integration was not accounted for by the peripheral defect; likewise, no significant correlations were found between speech discrimination in the better ear and the dominant ear. Strouse et al[44] conducted a study in individuals over the age of 60 with both normal-hearing and with moderate sensorineural hearing loss. Overall, the results indicated that as the difficulty of the test increased, so, too, did the REA.

The purpose of this study is, first of all, to evaluate the effect of cochlear hearing loss on the mechanisms of binaural integration. Secondly, it is to study the effect of the difficulty of the test on brain asymmetries by interhemispheric dominance. Finally, this study seeks to analyze the effect of age on CAP, in both subjects with normal hearing, as well as hearing-impaired individuals.

MATERIAL AND METHOD

Subjects

Eighty-eight right-handed subjects (40 males and 48 females) aged 35 to 72 were evaluated. The sample was divided into 4 groups according to age and hearing status. Groups 1 and 2 were made up of control subjects with normal hearing (n=44) with ages ranging from 35 to 59 and over the age of 60, respectively. Groups 3 and 4 comprised the experimental group consisting of hearing-impaired subjects (n=44) with the same age cohorts.

The auditory thresholds obtained from liminal tonal audiometry in the normal-hearing subjects were less than 30 dB HL for the octave-band intervals of 250 Hz to 8000 Hz.[45] The group of hearing-impaired subjects was selected according to the following criteria: *a)* auditory sensitivity greater than 30 dB HL; *b)* difference between air and bone conduction thresholds no greater than 10 dB HL; c) difference between thresholds of the right ear and left ear less than 15 dB HL; *d)* maximum speech discrimination (MSD) greater than 80% in both ears; and *e)* difference of less than 10% between the MSD obtained in the right and left ears. The group of hearing-impaired subjects was later subdivided according to the mean auditory threshold for the frequencies of 1, 2, 3, and 4 kHz. Three categories of hearing-impaired individuals were established; those with slight hearing loss with thresholds between 30 and 40 dB HL, moderate hearing loss with thresholds between 40 and 70 dB HL and severe hearing loss between 70 and 90 dB HL. Table 1 presents the mean liminal tonal threshold for the frequencies of 1, 2, 3, and 4 kHz, the speech reception threshold (SRT), and the percentage of MSD of the participants in this study. The clinical examination of these patients did not reveal any retrocochlear involvement or middle ear alterations. The laterality of all the participants was determined on the basis of the hand they prefer to use for writing and eating.

Material

The DDT was performed by means of a digital recording of the numbers from 1 to 9 with a female voice at normal vocal intensity. Each number was edited using the Sound Forge V5.0 software by Sonic Foundry, 1997. Each audio

Table 1. Mean (Standard Deviation) of the Liminal Tonal Threshold for the Frequencies of 1 kHz, 2 kHz, 3 kHz, and 4 kHz, Speech Reception Threshold and Maximum Speech Discrimination of the Group of Participants in this Study

	Tonal Threshold, dB HL		*Speech Reception Threshold, dB nHL*		*Maximum Discrimination, %*	
Auditory Sensitivity	*Right Ear*	*Left Ear*	*Right Ear*	*Left Ear*	*Right Ear*	*Left Ear*
Normal-hearing (n=44)	25.61 (1.95)	28.32 (1.82)	25.34 (1.02)	27.32 (1.25)	98.56 (1.78)	99.45 (1.64)
Slight hearing loss (n=14)	32.45 (2.20)	36.72 (2.35)	39.12 (1.54)	39.28 (1.70)	97.33 (1.98)	96.57 (1.61)
Moderate hearing loss (n=18)	49.28 (3.12)	52.63 (4.55)	57.10 (2.27)	55.25 (2.60)	91.15 (2.48)	87.78 (3.14)
Severe hearing loss (n=12)	74.52 (7.62)	79.84 (76.64)	81.67 (8.81)	83.33 (3.33)	89.33 (10.67)	81.33 (15.87)

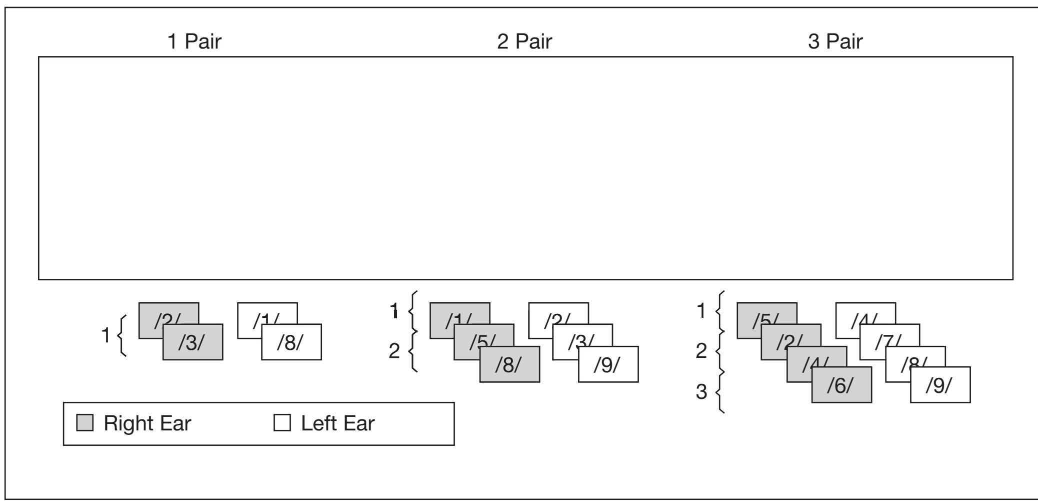

Figure 1. Composition of the scales of the dichotic digits test. In the upper part we see the oscillograms of the audio files for one block comprising a single pair. In the lower part we see the dichotically presented digits. In the middle of the graph, we see an example of a block with 2 pairs and to the right, an example of 3 pairs.

file was equalled for time, adding a silence to achieve 463 ms. This pause of silence corresponded with the sample for the number 7, given that this was the longest. All possible combinations of digit pairs were created without repeating a single pair. As represented in Figure 1, the pair was established as the 2 item set presented consecutively in the same ear. Between each pair of digits, there was 500 ms interstimuli interval. The blocks of 2 and 3 digit pairs were made by adding number pairs to the ones previously elaborated. The same number was never repeated within a single block. The position of the digit pairs within each block was established randomly; thus, each pair of numbers appeared in the first, second and third positions the same number of times throughout the entire scale. Finally, 3 groups of 9 blocks were created in which 2- and 3-digit pairs were counted one at a time. The final scale was created on the basis of the randomization of these 9 blocks that gave rise to a total of 27 blocks. Five seconds of silence were established between each block. An additional 10-block scale was created in order to familiarize the participant with the procedure. The training scales and tests together with a calibration tone of 1 kHz at 60 dB SPL were recorded on a compact disc (Samsung DVD±RW 18x Recorder Lightscribe Writemaster model SH-S182M).

Procedure

Prior to the DDT and in order to rule out any middle and inner ear conditions and possible retrocochlear injury, all participants underwent otoscopic examination, immittance acoustic measures, stapedial reflexes, and brainstem provoked auditory potentials. Auditory sensitivity was established in all the subjects by means of liminar tonal audiometry and speech testing. The DDT scales were presented by means of a compact disc player (Sony model D-NE240) and amplified through an audiometer (Grason-Stadler model 16) with over-the-ear TDH-39 headphones. The list of DL was administered at an intensity of 65 dB nHL for subjects with normal hearing and 35 dB higher than the SRT in the case of hearing-impaired subjects. Once the participants' understood how the testing procedure worked, the 27 blocks of dichotic number pairs were presented. Participants were asked to record the numbers presented to both ears without paying attention to the order of response.

Data Analysis

The results were analyzed by studying the number of presentation positions for each number within the pair. A measure was obtained for each subject of the scores according to the number of pairs under these conditions. The results were expressed as percentages of correct answers. The effects

Table 2. Mean (Standard Deviation) of the Percentages of Correct Answers Per Ear According to Item Difficulty, Hearing Status, and Age Group

	Normal-Hearing		*Hearing-Impaired*	
Group	*Right Ear*	*Left Ear*	*Right Ear*	*Left Ear*
35-59 Years (n=46)				
Easy	86.36 (14.62)	86.62 (9.65)	81.19 (28.56)	75.64 (16.90)
Medium	73.74 (15.61)	70.83 (19.41)	70.37 (27.96)	64.39 (18.61)
Difficult	62.96 (18.46)	55.13 (19.79)	64.74 (23.85)	52.99 (18.75)
>60 Years (n=42)				
Easy	79.08 (24.88)	70.59 (24.28)	77.47 (22.82)	55.87 (25.67)
Medium	68.95 (22.36)	63.89 (15.25)	66.67 (20.95)	48.56 (22.54)
Difficult	62.96 (18.46)	42.92 (17.78)	67.90 (16.37)	34.57 (19.58)

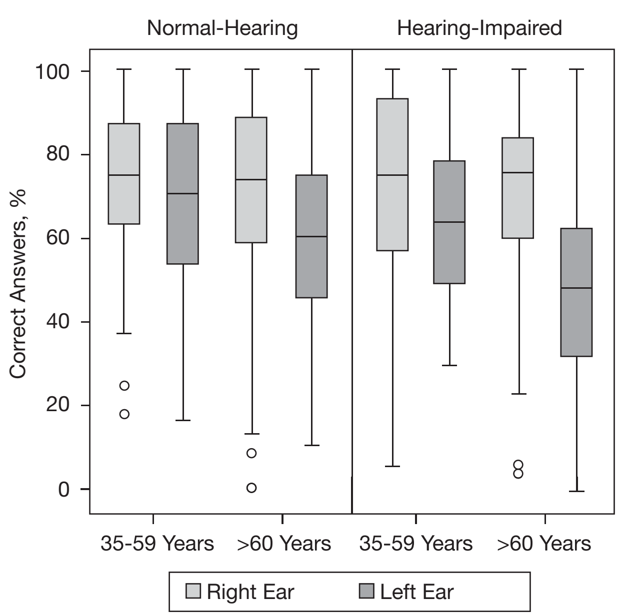

Figure 2. Graphs of the scores of correct answers, by hearing status, age group, and ear of presentation. The boxes represent the scores of 50% of the subjects. The horizontal line represents the mean percentage of correct answers.

of each subject's independent variables were analyzed; item difficulty was determined by the number of pairs and ear of presentation. Patient's age group and auditory status were studied as independent variables between subjects. The design consisted of 5×3×2×2 repeated measures. An analysis of the variance (ANOVA) was used to compare factors. Tukey's DHS test was used for subsequent analysis. The level of statistical significance was set to .05. Brain asymmetry was determined by means of the following equation (RE is the score of the right ear and LE corresponds to the left ear score)[46]:

$$LI=[(RE-LE)/(RE+LE)]\times 100$$

A positive LI reveals an REA; a negative LI, an advantage of the left ear (LEA), and an LI close to zero indicates symmetrical processing. The data analysis was performed using the SPSS statistical software package.[47]

RESULTS

Table 2 shows the mean and standard deviation of the percentages of correct answers in the recognition of digit pairs presented dichotically. Figure 2 presents the descriptive statistics by means of a box and whisker diagram of the data shown in Table 2. In general, higher mean scores of correct answers on digit recognition are attained by the right ear. In Figure 2, these differences are evident in the correct answer scores between ears. These differences are particularly obvious in the group of subjects over the age of 60 and in the group of hearing-impaired subjects.

The data presented in Table 2 and in Figure 2, as well as the results of the ANOVA revealed the major effects for the independent variables: ear of presentation (F[1.23]=33.182; *P*<.000), auditory status (F[1.23]=6.600; *P*<.011) and item difficulty (F[2.23]=37.675; *P*<.000). Age was significantly determinant (F[1.23]=19.933; *P*<.0001) in the ability to answer correctly. The a posteriori analysis with Tukey's test on the major effect of the item difficulty variable revealed significant differences between the 3 blocks of digit pairs. The items of 3 pairs were significantly more difficult than the 2-pair block (*P*<.0001) and these were significantly more difficult than the single-pair block (*P*<.0001).

The ANOVA performed on the data demonstrated a significant interaction between the participants' age and the ear of presentation (F[1.23]=8.719; *P*<.003). With increasing age, the scores in both ears fell. Nevertheless, this decrease in the scores was not the same in both ears. In subjects over the age of 60, the scores obtained in the left ear were significantly lower than the correct answers recorded in the right ear.

The analysis of the variance demonstrated a significant interaction between the patient's auditory status and the

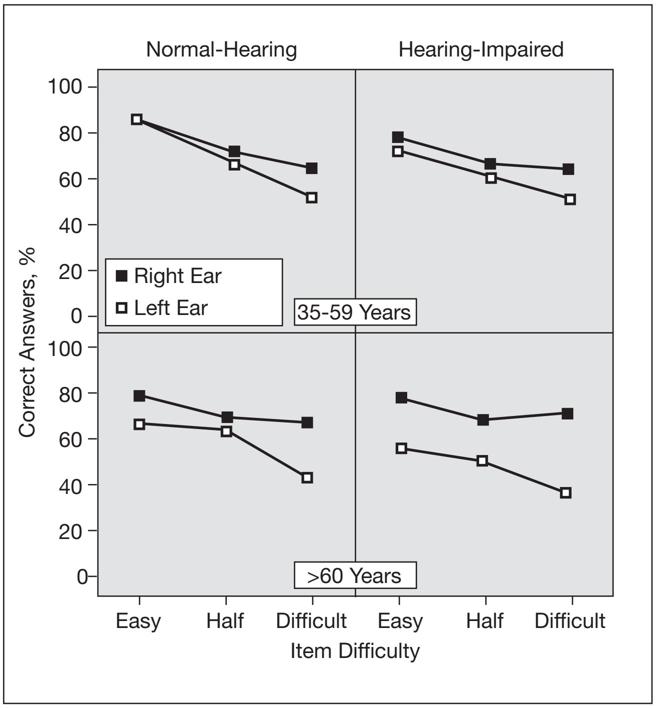

Figure 3. Percentages of correct answers of the 2 age groups depending on auditory status. On the left, the mean correct answers are given per ear in the participants with normal hearing. The column on the right represents the results obtained from the hearing-impaired group.

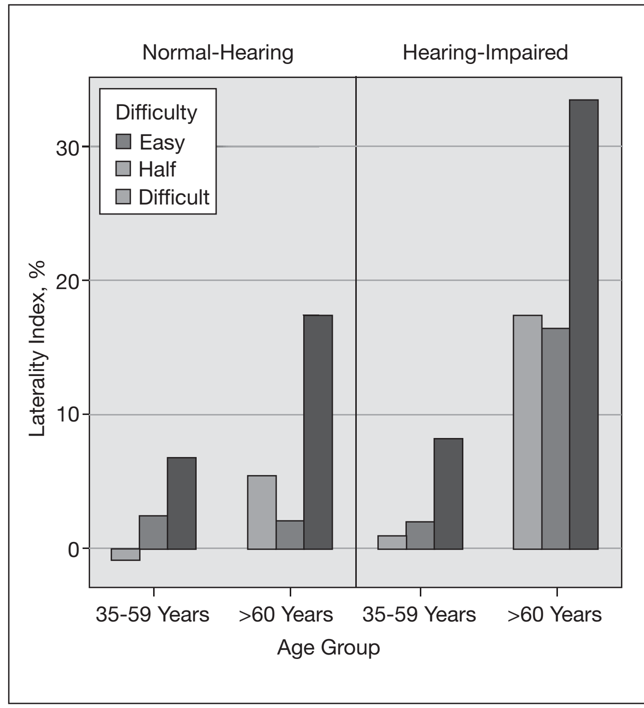

Figure 4. Laterality index for subjects with normal hearing and hearing-impaired individuals according to age group and item difficulty.

ear of presentation the items were presented to (F[1.23]=5.058; *P*<.025). Overall, the hearing-impaired subjects scored lower than the subjects with normal hearing. Depending on the subject's auditory status, the percentage of correct answers for the left ear was significantly lower than the correct answers recorded for the right ear.

Figure 3 provides a graphic illustration of the previously described interactions. In general, the scores in both ears are seen to decrease as item difficulty increases. On the left of Figure 3, the effect of ages is seen in the group of subjects with normal hearing. The interaction between age and ear in the group of individuals over 60 years of age indicates lower scores in the left ear. The interaction between auditory status and the ear of presentation is seen in Figure 3. The hearing-impaired subjects score lower than subjects with normal hearing on item recognition in the left ear.

Figure 4 presents the LI results. The ANOVA indicates a significant major effect for the age group variable (F[1.11]=7.974; *P*<.005). The LI obtained by the group of subjects over 60 years of age was significantly higher than the LI obtained by the group aged 35-59. No major effects were found for the auditory status and item difficulty variables. The interactions between the variables examined in the ANOVA for LI did not reveal significant interactions.

Figure 5 shows each individual's results according to age group and auditory status by means of a bivariant dispersion graph. The percentage of correct answers for the right ear is shown along the x-axis and the percentage of correct answers for the left ear appears along the y-axis. The subjects below the diagonal score higher on digits presented to the right ear and the subjects above the diagonal achieve higher recognition scores on items presented to the left ear. The dots above the diagonal represent symmetrical competences in binaural integration mechanisms. Figure 3 shows that the subjects with normal hearing display less dispersion and better scores on the ability to get the correct answers that the group of hearing-impaired people. In all the groups, the majority are situated below the diagonal, demonstrating a clear REA. In the group of normal-hearing individuals aged 35-59, 40% displayed an LEA; 53% had an REA; and 7% revealed no laterality preference. In the group of hearing-impaired subjects, 22% had an LEA and 78%, an REA. In the group of individuals with normal hearing over the age of 60, 25% presented an LEA; 71% exhibited an REA; and 4% had no lateralization preference. Thirteen percent of the hearing-impaired subjects presented an LEA and 83%, an REA. Four per cent (4%) of the subjects with normal hearing over the age of 60 did not display any asymmetry with respect to binaural integration.

A correlation was made between MSD scores and the percentages of correct answers on the DDT whenever the dominant ear could be determined by differences in monaural speech discrimination. The correlations between the ear with the better MSD and the dominant ear were not significant (*r*=0.306; *P*>.005).

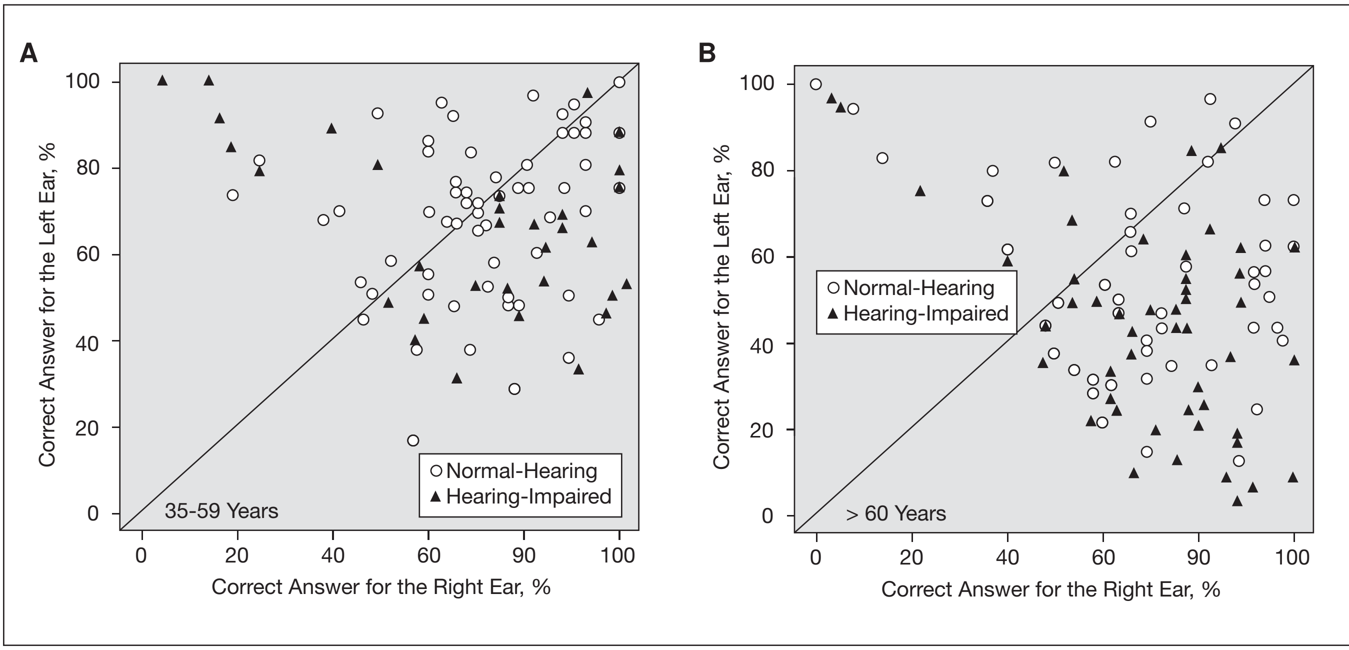

Figure 5. Bivariant dispersion graph of the individual correct answer scores for the right ear, on the x-axis, and, for the left ear, on the y-axis. A: the 35-59 year old age group. B: the over 60 age group.

DISCUSSION

The CAPD study is carried out by means of tests that are grouped into batteries of tests that include DL tests, among others. These tests are non-invasive diagnostic procedures that make it possible to examine the central auditory mechanisms of interhemispheric binaural integration. In this article, DDT in a population of subjects with normal hearing and individuals with hearing loss were studied. The percentage of correct answers was analyzed according to the ear of presentation, the difficulty of the test, subjects' age, and hearing status.

These results are consistent with the findings of previous research conducted in subjects with normal hearing in which an REA was systematically detected.[30,48-50] This study revealed 73% correct items for the right ear and 64% for the left ear, with a 9% difference in performance between both ears. Strouse et al,[43] in a group of subjects with a younger average age than in this study, obtained correct answer rates of 94% and 86% in the left and right ears, respectively, with a relative performance difference of 8% between both ears. This research replicates the results obtained by Musiek[13] for single-pairs, in which the rate of correct answers in the normal-hearing population or among those with cochlear hearing impairment was 90% or more and the differences between both ears were not greater than 2%.

Comparisons based on age showed better results in the 35-59 year old group than in the over 60 year old group, irrespective of the auditory status. The aging effect on DL has been established in several studies, which demonstrates that age entails greater REA at the expense of worse scores for the left ear.[34,51,52] This decrease in left ear recognition abilities might be interpreted as a dysfunction in the transfer of auditory information across brain hemispheres through the corpus callosum.[34,43,53-55]

The REA can be used to study the mechanisms of binaural integration. In this study, the younger group of patients was seen to have less of an REA, with a percentage of recognition of close to 100% on the less difficult items. The magnitude of the REA seen in the normal-hearing individuals over the age of 60 is consistent with the findings of other, earlier research.[34,43,53,54,56]

The results obtained in the hearing-impaired subjects differ significantly from those obtained in the control group of subjects with normal hearing. The hearing-impaired subjects: *a*) overall, score slightly worse than subjects with normal hearing; *b*) the asymmetries between the 2 ears are significantly greater; and *c*) the REA is greater, largely due to the worse scores obtained by the left ear. It is tempting to speculate that these differences in the hearing-impaired subjects are due to worse speech discrimination or to the differences between ears on the SRT and in the liminal tonal audiometry. Neither supposition is consistent with the lack of correlation between the scores obtained on the speech testing and the dominant ear. Be that as it may, the hearing defect does not entirely account for the greater magnitude of the REA in hearing-impaired subjects. This REA is hard to explain given that one would expect that it would affect DL in both the right ear and in the left ear in like measure, as well as that the dominant ear would have corresponded to the one having better auditory sensitivity and speech discrimination. This REA has also been observed in subjects with asymmetrical hearing loss, in whom the RE had worse hearing and speech discrimination.[57]

In subjects with hearing loss, thanks to a deficit in the ability to recognize stimuli in the left ear, the REA is consistent with the results obtained by other authors.[34,43,44,53,58,59] Martin et al[59] propose that the REA be redefined as a disadvantage of the left ear. The abolition of the left ear in DL in hearing-impaired subjects responds to an auditory processing strategy by focalizing attentional resources toward the right ear. This strategy makes it possible to reach a total binaural score similar to that of subjects with normal hearing and even higher. These observations are in line with the model of dichotic processing put forth by Jerger et al,[52] in which a CAP defect would lead to better scores when attention is focalized to a single ear, whereas a peripheral defect would affect both ears equally.

CONCLUSIONS

The results of this study of dichotic digit presentation can be summed up as:

1. The ability to recognize and correctly discern dichotically presented digits is lower in the left ear than in the right ear. These recognition abilities by the left ear decrease as differences in recognition between ears increase with the effect of aging, test difficulty, and auditory sensitivity.

2. The ability to answer correctly invariably decreases as task complexity increases. This decrease was more acute in the material presented to the left ear in older subjects, as well as in the hearing-impaired.

3. Hearing-impaired subjects exhibit a deficit or abolition of the competences in central auditory mechanisms of binaural integration and of verbal stimuli in the non-dominant ear.

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