Auditory processing in a patient with a unilateral lesion of the inferior colliculus

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Abstract
The role of the inferior colliculus (IC) in human auditory processing is still poorly understood. We report here the results obtained with a 12-year-old boy (FX) who suffered a very circumscribed lesion of the right IC without additional neurological damage. The child underwent an extensive battery of psychophysical hearing tests. Results revealed normal peripheral auditory functioning, bilaterally. Furthermore, masking-level differences and frequency-pattern recognition were normal for each ear. When the right ear was stimulated, behavioural tests assessing central auditory processing yielded normal results. However, when the left ear was stimulated, speech recognition in the presence of a competing ipsilateral signal and duration-pattern recognition were impaired. Similarly, performance on two dichotic speech recognition tests was poor when the target stimulus was presented in the left and the competing signal in the right ear. Finally, sound-source localization in space was deficient for speakers located on the side contralateral to the lesion. The pattern of results suggests that auditory functions such as recognition of low-redundancy speech presented monaurally, recognition of tone duration patterns, binaural separation and integration, as well as sound-source localization in space, depend on the integrity of the bilateral auditory pathways at the IC level.

Introduction
In order to perceive complex sounds, the auditory system must fuse and segregate auditory signals. Numerous studies have attempted to understand the underlying mechanisms, on the one hand by establishing associations among structures and/or physiological mechanisms with performance (e.g. Cariani & Delgutte, 1996; Litovsky & Yin, 1998; Furst et al., 2000) and, on the other, by examining in animals how ablation of a structure affects behaviour (e.g. Heffner & Masterton, 1975; Whitfield, 1979; Jenkins & Masterton, 1982).

In humans, the principal drawback of the lesion approach, derived from case studies, is that the lesion is rarely circumscribed to only affect auditory processing. This is particularly true of the inferior colliculi (IC), midbrain obligatory relays in auditory signal transmission. Studies in animals (see Winer & Schreiner, 2005 for review) are tenuous because the findings, especially for higher-level functions such as speech, are not transferable to humans.

In humans, bilateral lesions of IC resulted in central deafness (Musiek et al., 2004) or auditory agnosia (Johkura et al., 1998), while partial lesions (Hoistad & Hain, 2003) were inconclusive. Unilateral lesions further allow the assessment of precise dissociations in auditory functions between the lesioned and intact side in the same subject. Some did not show any changes in pure tone detection or speech recognition in silence (Bognar et al., 1994; Musiek et al., 1994a; Litovsky et al., 2002) following an IC lesion, while one reported a severe to profound deficit in speech recognition following a diffuse unilateral lesion when stimuli were presented to the contralateral ear (Fischer et al., 1995).

Release from masking and speech perception in noise, tested binaurally, were unimpaired following diffuse lesions that included IC (Litovsky et al., 2002; Lynn et al., 1981). Paradoxically, the subject in the Litovsky et al. (2002) study reported having difficulties with speech perception in noisy environments in his daily life. In fact, the monaural pathway, which drives mainly contralateral IC (Oliver et al., 1997), is involved in the improvement of signal-to-noise ratio through filtering or critical-band selection (Fletcher, 1940; Zerlin, 1986; Burrows & Barry, 1990), suggesting that the IC is involved in speech perception in noise.

Data on dichotic integration are also somewhat inconsistent. Musiek et al. (1994a) reported that a lesion affecting mostly left IC resulted in abnormal performance bilaterally. Fischer et al. (1995), however, observed reduced performance for the contralateral ear while Bognar et al. (1994) reported poorer performance in the ipsilateral one.

Finally, sound localization, following a unilateral IC lesion that included the rostral lateral lemniscus, was shown to be impaired, predominantly on the contralateral side (Litovsky et al., 2002).

In summary, no general auditory pattern has been unequivocally related to IC. These inconsistencies may be attributable to accompanying diffuse midbrain lesions or to differences in tasks used across studies. Moreover, performance on tasks involving monaural recognition of low-redundancy speech stimuli, frequency and duration pattern recognition for tonal stimuli, and binaural separation of stimuli
have not been studied in individuals with circumscribed unilateral IC lesion.

Here, we report data derived from psychophysical experiments carried out monaurally and binaurally in a high-functioning individual who sustained a circumscribed haemorrhage in the right IC.

Materials and methods

Subject

FX is a 12-year-old francophone boy who at the age of 9 years suffered a traumatic haemorrhagic lesion that was strictly limited to the right IC (see Fig. 1). The child did not spontaneously complain of hearing loss. Furthermore, he did not report difficulties recognizing speech, music or environmental sounds nor did he report any problem localizing sounds in space. According to his medical file, the neurological examination was within normal limits.

Procedure

All perceptual tests were carried out in a standardized audiometric sound-attenuated chamber. The stimuli were presented via TDH39 earphones (Telephonics Corporation, Huntingdon, NY). Except for the sound-source localization task, a calibrated GSI-10 (Grason Stadler Inc, Madison, Wisconsin) clinical audiometer was used to generate the test stimuli.

To test the integrity of peripheral pathways, we measured distortion product otoacoustic emissions, acoustic immitance, pure-tone and speech detection thresholds. Psychophysical tests included speech recognition in silence as well as six tests commonly used to evaluate general auditory processing abilities: binaural interaction, pattern recognition and temporal sequencing (frequency and duration), monaural separation and/or closure, binaural separation and binaural integration (Bellis, 2003). In addition, the subject completed a sound-source localization task. The test battery was administered on two different days in order to maintain the subject’s motivation and to minimize the effects of fatigue.

Where applicable, the results obtained from FX were compared to established normative data. Furthermore, prior to testing FX, two neurologically intact subjects with normal hearing completed the test battery. This was done to ensure that the equipment was functioning properly. The results of both subjects were within normal limits.

Peripheral audiological functioning

Distortion product otoacoustic emissions were measured in both ears at 1.5, 2, 3, 4 and 6 kHz. Acoustic immitance was also assessed bilaterally. More specifically, acoustic reflexes were measured at three test frequencies (500, 1000 and 2000 Hz) using both ipsi- and contralateral stimulation. Pure-tone detection thresholds were evaluated independently in each ear at 0.25, 0.5, 1, 2, 4 and 8 kHz. Speech reception thresholds were obtained using a list of French bisyllabic words.

General auditory functioning

Speech perception in silence

The speech recognition task consisted of phonetically balanced French words. The stimuli were presented monaurally at a conversational level (50 dB Hearing Level) without any competing signal. Twenty-five words were presented to each ear. The subject was asked to listen and repeat what he had heard.

Binaural interaction

To assess binaural interaction, the masking-level difference (MLD) test was administered (Hirsh, 1948; Licklider, 1948). This test comprised three conditions. In the first condition, a 500 Hz pure-tone signal and a white-noise masking signal were both presented bilaterally. The pure tones (S) and the masking noises (N) were both presented identically at the two sides (condition SoNo). In the second condition, one of the pure tones was presented 180° out of phase with the other while the masking noises remained identical (condition S

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Finally, in the third condition, the two pure tones were presented in phase whereas the two masking noises were inverted (presented 180° out of phase; condition: SoNp). The MLD is defined as the difference in the binaural detection threshold between the condition SoNo, where the tones and the noises are presented in phase bilaterally, and the S

The results obtained from FX were compared to the normative values that have been reported by investigators who have used a GSI-10 audiometer to measure the MLD (Harris et al., 1992). According to these authors, an MLD of <10.1 ± 2.6 dB in the SpNo condition, or a value of <13.7 ± 2.8 dB in the SoNp condition, would indicate poor release from masking.

When the relative phase of either the signal or the noise is altered, a ‘release from masking’ normally occurs.

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Tone-pattern recognition

Two tasks were administered monaurally: the frequency-pattern sequence (FPS) test (Pinheiro & Ptacek, 1971) and the duration-pattern sequence (DPS) test (Pinheiro & Musiek, 1995).

Fig. 1. (a) Coronal, (b) sagittal and (c) axial MRIs showing a restricted lesion of the right inferior colliculus (arrow). R, right; L, left (from Champoux et al., 2006).
In the FPS test, two pure tones (a low-pitched tone of 880 Hz and a high-pitched tone of 1122 Hz) were used to create tonal sequences consisting of three tones each (e.g., low–low–high). Sixty tonal patterns were presented in each ear. After each pattern, the subject had to identify the tonal pattern using either a verbal or a hummed response. According to normative data, recognition scores $< 78\%$ correct responses (i.e., 2 SD below the mean) are indicative of an abnormally low performance (Musiek, 1994b).

The DPS test consisted of the presentation of three 1000-Hz tonal pulses of a duration of 500 ms (long tone) or 250 ms (short tone). A total of 30 tonal patterns were presented to each ear. After each pattern, the subject was asked to verbally identify the tonal pattern that was presented (e.g., short–long–short). According to established norms, a recognition score $< 73\%$ correct responses (i.e., 2 SD below the mean) is considered to be abnormally low (Musiek, 1994b).

Monaural separation or closure ability

This was tested by means of a recognition task consisting of low-redundancy speech stimuli presented monaurally. The French-Canadian version (Normandin, 1990) of the synthetic-sentence identification in ipsilateral competing message (SSI-ICM; Jerger & Jerger, 1974) was used to obtain monaural speech recognition scores in the presence of a competing speech signal channeled to the same ear. This test consists of presenting meaningful, continuous competing discourse and 10 episodic nonsense target sentences. The subject was asked to ignore the continuous discourse and to repeat the target sentence. The competing verbal message was presented at three different signal-to-noise (S/N) ratios: $+10$, $0$, and $-10$ dB. Based on French-Canadian norms, scores $< 83\%$ correct responses (i.e., 2 SD below the group mean) at a S/N ratio of $-10$ dB are considered to be abnormal.

Dichotic listening ability

The ability to process an auditory message in one ear while ignoring a different message simultaneously received in the opposite ear (i.e., binaural separation) was evaluated by means of the French-Canadian version (Normandin, 1990) of the synthetic-sentence identification in contralateral competing message test (SSI-CCM; Jerger & Jerger, 1974, 1975). The stimuli and procedure were the same as those used in the SSI-ICM test described above. However, in the SSI-CCM test, the continuous discourse was channeled to one ear while the target sentence was channeled to the other ear. The competing stimulus was presented at various S/N ratios relative to the target stimulus. Adults with normal auditory abilities tend to obtain close to 100% correct recognition scores even at a high S/N ratio (i.e., $-40$ dB; Jerger & Jerger, 1974, 1975). However, because large differences can be found among individuals, Bellis (2003) found that it is more informative to compare the performance of the two ears within subjects than to analyse the absolute performance of each ear against some standard measure.

A second dichotic speech test was administered to evaluate the subject’s ability to process information presented simultaneously to both ears (i.e., binaural integration). The French-Canadian version (Normandin, 1990) of the staggered spondaic word test (SSW; Katz, 1968) was used. In this test, two spondaic words were separately presented to each ear in such a manner that the last half of the first spondee and the first half of the second spondee were received simultaneously. Word errors were scored for four different listening conditions, each comprising 40 trials, left and right ear in competing and noncompeting modes referring to the presentation of the same or a different word to the ears. The results were scored according to ‘order’ effect, pertaining to errors on the first or second syllable of the spondee, and ‘ear’ effect, referring to errors that occur when the target stimulus was presented in the right vs. the left ear.

Sound-source localization in space

This task was administered to test the subject’s ability to localize a sound-source on the horizontal plane. The apparatus consisted of 13 loudspeakers (Radio Shack Minimum 7, matched for level) that were positioned horizontally at $15^\circ$ intervals on a perimeter spanning $180^\circ$ in the frontal hemifield. The subject was sitting comfortably in a chair facing the 13 loudspeakers, which were positioned in a semicircle in front of him at a distance of 72 cm from the nodal point of the head. The chair was adjusted so that the loudspeakers were at the subject’s ear level. Each loudspeaker was identified by a number. The testing chamber was well-lit, and the subject was aware of the locations of the 13 loudspeakers.

The test stimulus was a 100-ms broadband noise, delivered at 60 dB sound pressure level and calibrated at a position corresponding to the centre of the subject’s head. A Tucker-Davis Technologies (TDT) System-II was used to generate the stimuli. The output of the sound generating equipment was fed through a 16-bit DAC to programmable filters, amplified (TEAC), and presented to the loudspeakers through 13 independent channels. The interstimulus interval was fixed at $5.5$ s. After each trial, the subject was asked to report verbally, by calling out the number of the loudspeaker, from which loudspeaker the noise had been presented. Fifty-two trials (four presentations from each of the 13 loudspeakers) were administered. Patient and controls gave their written consent to participate in the study. The study was approved by the Ethics Review Board of Université de Montréal.

Results

Peripheral audiological functioning

Otoscopic examination revealed normal ear drum appearance bilaterally. Similarly, acoustic immittance measurements were within normal limits bilaterally. Specifically, the tympanograms showed normal compliance, volume and pressure, bilaterally. Furthermore, acoustic reflexes were normal at all three test frequencies, suggesting that the lower neural relays of the auditory system functioned normally. Distortion production otoacoustic emissions were present and within normal limits in both ears, at all frequencies tested: 1.5, 2, 3, 4 and 6 kHz.

Pure-tone detection thresholds, at octave frequencies ranging from 250 to 8000 kHz, were also well within normal limits in both ears (see Fig. 2a). The same was true for speech reception thresholds (0 dB HL). Taken together, the results of the routine audiometric test battery indicate normal functioning of the peripheral auditory system.

General audiological functioning

Speech recognition in silence

The subject’s performance on the phonetically balanced French word-recognition tasks presented at a conversational level (50 dB HL) without masking noise was perfect for each ear (see Fig. 2b).

Binaural interaction

The results obtained on the MLD test are displayed in Fig. 3. As can be seen, FX showed no significant difference with respect to controls as regards release of masking, although his performance was...
somewhat above average, in either the SoN\(n\) condition (12.5 dB) or the S\(n\)No condition (15 dB).

Frequency and duration tone pattern recognition

The subject’s mean score on the two pattern recognition tests are summarized in Fig. 4.

On the FPS test, FX obtained perfect scores bilaterally. These performance levels were independent of the response mode (hummed or spoken).

In contrast, the responses obtained on the DPS test were less than optimal, especially for stimuli presented to the left ear. There was a difference of 30% between left ear (43.3%) and right ear (73.3%), favouring the latter.

Monaural separation or closure

The subject’s mean scores obtained on the SSI-ICM test are displayed in Fig. 5. FX performed normally in all conditions where the test stimuli were channeled to the right ear. In contrast, his performance decreased considerably when the stimuli were presented to the left ear. It may be recalled that FX obtained perfect scores in each ear on the

Fig. 2. FX’s (a) audiogram and (b) performance on the phonetically balanced word recognition test. O, right ear; X, left ear.

Fig. 3. FX’s performance on the masking level difference test. FX’s scores (open columns) are compared to normative data (solid columns).

Fig. 4. FX’s performance on the frequency- and the duration-pattern sequence tests, using either a verbal (V) or a hummed (H) response. Right ear, solid columns; left ear, open columns. *Responses were > 2 SDs below the group mean.

Fig. 5. FX’s performance on the sentence identification tasks. On the monaural task (SSI-ICM), the competing verbal message was presented in the same ear at S/N ratios of +10, 0 and −10 dB relative to the target sentences. In the dichotic condition (SSI-CCM), the competing message was presented in the ear contralateral to the target sentences at S/N ratios of −20, −30 and −40 dB. Right ear, solid columns; left ear, open columns. *Responses were > 2 SDs below the group mean.
monaural word recognition tasks in the absence of a competing stimulus (see audiometric test, Fig. 2).

On the SSI-ICM test, significant differences in performance were observed between the two ears at all three S/N ratios tested. Even at the most favourable S/N ratio, an ear difference of 60% was observed when the test sentences were presented in the right ear.

Dichotic listening ability

Differences between left and the right ear performance were also observed on the SSI-CCM test (Fig. 5). In this test, FX obtained perfect scores in both ears at a low S/N ratio (−20 dB). A decrease of 10 dB in the S/N ratio resulted in a mild advantage (10%) for the right ear. This right ear advantage increased significantly (40%) with an increasing S/N ratio (−40 dB).

The results obtained on the SSW test are shown in Fig. 6. The percentage error rate in this figure is plotted as a function of the four test conditions: right-ear noncompeting (RNC), right-ear competing (RC), left-ear competing (LC) and left-ear noncompeting (LNC). FX’s result (solid bars) are compared to age norms (open bars). It can be seen that FX made significantly more errors (2 SD below the group mean) in the left than in the right ear in both stimulus conditions, attesting once more to a right ear advantage.

Sound-source localization in space

Figure 7 illustrates FX’s performance on the sound-source localization task. In this figure, the subject’s responses are plotted as a function of the spatial location of the sound source in the horizontal plane. The percentage of errors is displayed as a function of the position of the loudspeakers that represent the sound source. As shown, FX was very accurate in localizing sound sources in the right frontal hemifield (0° to 90°). His accuracy, however, decreased considerably when the sound sources were located in the left hemifield. In the latter condition, he made twice as many errors (error rates: left, 45.83%; right, 20.83%). The error rate was highest (>60%) for sound sources located at 60° in the left hemifield. The data of the two control subjects, tested to ensure that the equipment was functioning properly, are not shown because their performance was close to perfect at every location.

Discussion

To assess the role of the IC in human auditory processing, a battery of auditory tests was administered to a 12-year-old boy (FX) who presented a circumscribed lesion of the right IC without additional neural damage. As the neuro-maturation of the auditory system of a 12-year-old is nearly complete (Bellis, 2003), it can be assumed that the results obtained from FX apply to an adult population. Indeed, the pattern of functions that were spared is consistent with that found in normal adults, whereas his errors are similar to those displayed by adult patients who have sustained a lesion of the central auditory nervous system (see Bellis, 2003 for review). For a more detailed discussion, the results are regrouped according to the functions tested.

Peripheral audiological functioning

Tonal detection thresholds and speech recognition in the absence of competing auditory input were normal for both ears. The results are consistent with those obtained in other case studies (Bogner et al., 1994; Musiek et al., 1994a; Litovsky et al., 2002) but they are at odds with the findings of Fischer et al. (1995) who observed a decrement in speech recognition in the ear contralateral to a unilateral lesion of the IC which was, however, more diffuse.

Binaural interaction

Consistent with the findings of Litovsky et al. (2002) and Lynn et al. (1981), who reported unimpaired performance on binaural interaction tasks in patients with upper midbrain lesions, FX’s results on the MLD task indicated normal release from masking in all conditions. Our results confirm that a circumscribed lesion limited to the IC, an upper midbrain structure, does not affect this auditory function.

Frequency- and duration-pattern recognition

FX was perfectly able to perform the FPS test regardless of the response mode (verbal or hummed). This result suggests that a lesion of the IC does not disrupt frequency-pattern perception.

In contrast, duration-pattern recognition was found to be deficient. FX showed a marked decrement in performance when the stimuli were presented to the left ear (i.e. the ear contralateral to the lesion) as compared to the right ear.

In recent work conducted with animals, the IC monaural pathway has been associated with pattern recognition (Oertel & Wickesberg, 2002) and sound-duration selectivity (Casseday et al., 2002). Given that FX’s performance in the FPS task suggests that pattern recognition capabilities were spared, results in the DPS task tend to confirm more specifically a role for the IC in duration selectivity.
To our knowledge, such a finding has never been reported in humans.

**Monaural separation or closure**

While FX’s ability to detect pure tones and speech presented in quiet was normal, his performance was clearly deficient when the speech stimuli were embedded in competing sounds. In the SSI-ICM test, FX had great difficulty separating the speech signals. Again, he performed more poorly when the signals were presented in the left than in the right ear. These results support the notion that critical-band properties emerge at the level of the IC (Zerlin, 1986; Burrows & Barry, 1990). The observation that reducing the redundancy of the speech stimuli presented monaurally had a deleterious effect on FX’s performance when the signal was presented to the ear contralateral to the lesion suggests that the IC plays a role in monaural processing of separation or closure tasks.

**Dichotic listening abilities**

Similar results were obtained in the dichotic condition where the competing signal was presented in the ear contralateral to the one that received the target stimulus (e.g. in the SSI-CCM test at a S/N ratio of −40 dB). Again, there was a drop in performance with left ear presentations. Our findings suggest that binaural separation may require, to some extent, the integrity of the IC. More specifically, they indicate that a unilateral lesion of the IC results in a deficit in the ear contralateral to the lesion.

In the SSW task, FX showed a significant decrement in performance when a competing message was presented in the right ear and the target signal was presented in the left ear (i.e. ‘LC condition’, shown in Fig. 6). This finding indicates that the IC also participates in binaural integration of speech. This observation is in agreement with previous data that related poor performance in the ear contralateral to an IC lesion (Fischer et al., 1995).

**Sound-source localization in space**

FX’s ability to locate a sound source on the horizontal plane was impaired. This was more marked when the stimuli were presented in the hemisphere contralateral to the lesioned side. These results are congruent with findings in animals (i.e. Jenkins & Masterton, 1982; Kelly & Kavanagh, 1994; Kelly et al., 1996) as well as with observations in a human subject with unilateral midbrain lesions including the IC (Litovsky et al., 2002), thus confirming the role of the IC in sound-source localization in space.

**Conclusion**

The aim of the present study was to gain a better understanding of the role of the IC in human auditory processing. The pattern of results obtained from our subject suggests that the integrity of the IC is critical for the processing of monaural low-redundancy speech, duration-pattern recognition of tonal sequences, binaural separation, binaural integration and sound-source localization in space. The results are consistent with, and extend, previous findings by showing that a circumscribed unilateral lesion of the IC is associated with impaired high-level auditory processing in the ear contralateral to the lesion.

Our findings also confirm that the IC is not involved in peripheral auditory processing. Tonal detection thresholds, frequency-pattern recognition and MLDs were normal, bilaterally, as was speech recognition in the absence of competing auditory input.

Although the lack of deficits in these functions could arguably be attributed to some form of neural reorganization that may have taken place in the time between the insult and the testing session, the pattern of results is consistent with expectations based on previous work in this area.

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**Abbreviations**

DPS, duration-pattern sequence; FPS, frequency-pattern sequence; HL, Hearing Level; IC, inferior colliculus; MLD, masking-level difference; S/N, signal-to-noise; SSI-CCM, synthetic-sentence identification in contralateral competing message; SSI-ICM, synthetic-sentence identification in ipsilateral competing message; SSW, staggered spondaic word.

**References**


