Reduced visual discrimination in cochlear implant users
Christine Turgeon\textsuperscript{a,b}, François Champoux\textsuperscript{a,b,d}, Franco Lepore\textsuperscript{a} and Dave Ellemberg\textsuperscript{a,c}

The aim of the study was to investigate low-level visual function in cochlear implant users. Spatial frequency discrimination was assessed in 16 adults with normal hearing and 18 adults with profound deafness who had a cochlear implant. Thresholds were measured with sinusoidal gratings using a two-alternative temporal forced-choice procedure combined with an adaptive staircase. Cochlear implant users had significantly poorer spatial frequency discrimination compared with normal hearing participants. Therefore, auditory privation leads to substantial changes in this particular visual function and these changes remain even after the restoration of hearing with a cochlear implant. NeuroReport 23:385–389 © 2012 Wolters Kluwer Health | Lippincott Williams & Wilkins.

Keywords: cochlear implant, deafness, frequency discrimination, vision

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Received 4 January 2012 accepted 7 February 2012

Introduction
Sensory deprivation induces extensive brain reorganization, and deprivation of a sensory modality can alter the neuronal responses in the remaining modalities. For example, event-related potentials show enhanced activation of the anterior temporal areas in deaf individuals compared with hearing individuals [1,2]. Further, MRI demonstrates activation in the auditory cortex of congenitally deaf individuals in response to visual stimuli such as moving dot patterns and moving sinusoidal gratings [3,4]. Several authors suggest that brain reorganization induced by sensory deprivation leads to behavioral changes in numerous visual tasks. In the case of early auditory deprivation, there is some debate over whether profound deafness results in visual deficits or an enhancement in visual performance [5]. Some studies have documented improved visual processing in the peripheral visual field of deaf individuals. Compared with hearing individuals, they are faster and more accurate in detecting the direction of moving visual stimuli [1,6], they are better at detecting an increment in luminance [7], and they have enhanced visual attention in the peripheral visual field [3,8,9]. In contrast, other studies suggest that deafness leads to a deterioration of some visual functions. For example, higher visual temporal thresholds [10] and poorer visual resolution [11,12] have been reported in deaf individuals. These findings suggest that auditory stimulation during development may play a role in the development and maturation of certain visual functions, and that the lack of auditory input may ultimately lead to an enhancement in higher level functions such as visual attention and deterioration in low-level visual functions.

It is now possible to partially restore hearing in deaf individuals through the insertion of a cochlear implant. This device bypasses the missing or damaged hair cells in the cochlea by directly stimulating the neurons of the auditory nerve and converts auditory signals into electrical impulses. Only a few studies have investigated visual functions in deaf individuals with a cochlear implant, and those that did were mainly interested in higher-level visual attention. In contrast to what is reported for higher-level visual tasks in deaf individuals, children with cochlear implants perform more poorly on tasks of visual attention compared with normally hearing participants [13,14]. Further, using a change blindness paradigm, Bottari et al. [15] found that deaf individuals with a cochlear implant were less sensitive to visual changes compared with deaf participants who did not have a cochlear implant. To date, nothing is known about the development of lower-level visual functions in deaf individuals with a cochlear implant.

The aim of the present study was to investigate low-level visual functions in deaf individuals with a cochlear implant. Spatial frequency discrimination is known to represent a fundamental building block of visual perception and it is essential for the analysis of fine details in a visual scene [16]. Therefore, we compared spatial frequency discrimination in normal hearing participants and in individuals with a cochlear implant.

Materials and methods
Participants
Sixteen adults with normal hearing (mean age = 26 years) and 18 adults with profound deafness and a cochlear implant (mean age = 36 years) participated in the study. For inclusion in the study, normal hearing participants were required to pass an audiometric test. Pure-tone detection thresholds were assessed using an adaptive method at 250, 500, 1000, 2000, and 4000 Hz. They were assessed...
independently with an intra-auricular earphone for each ear. All participants had detection thresholds below 25 dB HL at every frequency, which corresponds to normal hearing. Middle-ear function was assessed using a Grason-Stadler GSI 38 tympanometer (GSI Grason-Stadler, Milford, Massachusetts, USA) and all normally hearing individuals had normal mobility of the eardrum and normal middle-ear function.

The cochlear implant users suffered from severe-profound bilateral deafness before their surgery. All had progressive hearing loss that had started from birth or infancy and was present for a significant period time before implantation, and all used oral language as a primary mode of communication. Pure-tone detection thresholds were assessed using an adaptive method at 250, 500, 1000, 2000, and 4000 Hz in a free field at a distance of 1 m. This group presented detection thresholds that were generally above 40 dB HL for all frequencies tested, corresponding to what is generally reported in the literature [17]. The clinical profile of each cochlear implant user is presented in Table 1. None of the participants had learning disabilities or other known medical conditions. All the participants had normal or corrected-to-normal vision as determined with the Snellen eye chart (model R.J.’s) at a distance of 10 ft. All participants were unaware of the nature of the experiment and they gave written informed consent in accordance with the University of Montreal’s Ethics Board. Recruitment was made possible with the collaboration of the Centre de Recherche Interdisciplinaire en Réadaptation du Montréal Métropolitain/Institut Raymond-Dewar and the Centre de Réadaptation en Déficiences Physiques Le Bouclier.

Table 1  Clinical profile of the cochlear implant users

<table>
<thead>
<tr>
<th>Age</th>
<th>Etiology of deafness</th>
<th>Number of years with CI</th>
<th>Age at implantation (years)</th>
<th>Side of the implant</th>
<th>Aided thresholds with implanta</th>
<th>Preimplant hearing thresholds (R/L)b</th>
<th>Type of cochlear implant</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>Congenital</td>
<td>2</td>
<td>18</td>
<td>L</td>
<td>37</td>
<td>&gt;110/110</td>
<td>Cochlear-Freedom Nucleus</td>
</tr>
<tr>
<td>22</td>
<td>Congenital</td>
<td>6</td>
<td>16</td>
<td>L</td>
<td>40</td>
<td>&gt;120/97</td>
<td>Neurolec-Saphyr CX</td>
</tr>
<tr>
<td>25</td>
<td>Congenital</td>
<td>5</td>
<td>30</td>
<td>L</td>
<td>33</td>
<td>107/120</td>
<td>Advances Bionic-Claron</td>
</tr>
<tr>
<td>45</td>
<td>Congenital</td>
<td>4</td>
<td>41</td>
<td>L</td>
<td>35</td>
<td>95/103</td>
<td>Cochlear-Freedom Nucleus</td>
</tr>
<tr>
<td>46</td>
<td>Congenital</td>
<td>5</td>
<td>41</td>
<td>L</td>
<td>27</td>
<td>95/93</td>
<td>Advances Bionic-Claron</td>
</tr>
<tr>
<td>22</td>
<td>Congenital</td>
<td>6</td>
<td>16</td>
<td>L</td>
<td>15</td>
<td>&gt;117/93</td>
<td>Cochlear-ESPirit 3G</td>
</tr>
<tr>
<td>44</td>
<td>Congenital</td>
<td>1</td>
<td>43</td>
<td>L</td>
<td>33</td>
<td>117/117</td>
<td>Cochlear-Freedom Nucleus</td>
</tr>
<tr>
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<td>Congenital</td>
<td>2</td>
<td>28</td>
<td>L</td>
<td>32</td>
<td>93/100</td>
<td>Advances Bionic-Claron</td>
</tr>
<tr>
<td>27</td>
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<td>2</td>
<td>25</td>
<td>L</td>
<td>22</td>
<td>&gt;107/120</td>
<td>Cochlear-Freedom Nucleus</td>
</tr>
<tr>
<td>22</td>
<td>Unknown</td>
<td>12</td>
<td>10</td>
<td>R</td>
<td>27</td>
<td>&gt;120/120</td>
<td>Cochlear-ESPirit 3G</td>
</tr>
<tr>
<td>30</td>
<td>Meningitis</td>
<td>22</td>
<td>8</td>
<td>R</td>
<td>40</td>
<td>&gt;120/120</td>
<td>Cochlear-Freedom Nucleus</td>
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<tr>
<td>55</td>
<td>Ototoxicity</td>
<td>3</td>
<td>52</td>
<td>L</td>
<td>23</td>
<td>68/97</td>
<td>Cochlear-Freedom Nucleus</td>
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<tr>
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<td>2</td>
<td>22</td>
<td>L</td>
<td>23</td>
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<tr>
<td>51</td>
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<td>50</td>
<td>L</td>
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<td>110/110</td>
<td>Advances Bionic-Claron</td>
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<tr>
<td>48</td>
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<td>2</td>
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<td>L</td>
<td>18</td>
<td>118/107</td>
<td>Advances Bionic-Claron</td>
</tr>
<tr>
<td>38</td>
<td>Congenital</td>
<td>2</td>
<td>36</td>
<td>R</td>
<td>27</td>
<td>103/106</td>
<td>Advances Bionic-Claron</td>
</tr>
<tr>
<td>42</td>
<td>Unknown</td>
<td>4</td>
<td>38</td>
<td>R</td>
<td>22</td>
<td>88/88</td>
<td>Cochlear-Freedom Nucleus</td>
</tr>
<tr>
<td>39</td>
<td>Congenital</td>
<td>2</td>
<td>37</td>
<td>R</td>
<td>38</td>
<td>101/120</td>
<td>Cochlear-Freedom Nucleus</td>
</tr>
</tbody>
</table>

CI, cochlear implant; L, left; MPT, mean of pure-tone; R, right.

aMPT = 500, 1000, 2000 Hz.
bMPT = 500, 1000, 2000 Hz; > no measurable response at the limit of the audiometer for one of these frequencies (500, 1000, 2000 Hz).
Montreal, Quebec, Canada) and a Mactintosh OS X (version 10.5.5; Apple Inc., Cupertino, California, USA) computer. The stimuli were displayed using a linearized lookup table (calibrated with a Colour Vision Spyder 2 Pro; Datacolor, Lawrenceville, New Jersey, USA) and were presented on a 19-inch View Sonic G90/B CRT (View Sonic, Walnut, California, USA). The maximum luminance was 100 cd/m², the frame refresh rate was 85 Hz, and the resolution was 1024 × 768 pixels.

Frequency discrimination thresholds for each condition (low and high frequencies) were determined using a two-alternative temporal forced choice procedure combined with an adaptive staircase. For each trial, one interval presented a Gabor with the reference frequency, whereas the other presented a Gabor with the probe frequency. The presentation was randomized and the two Gabor were separated by a 500 ms interstimulus interval. Each experiment was preceded by a training phase to ensure that the participant understood the instructions. The first presentation of a probe frequency was four cycles per degree above the spatial frequency of the reference grating. Step size was subsequently adjusted according to Levitt’s [18] transformed 2-down 1-up staircase. Step size changed by 50% until the first reversal and then by 25%. On the way up, step size changed by 12.5%. An experimental session terminated once six response reversals had been recorded for a specific frequency. No feedback was provided. A subsequent pair was only presented once the user response was received, allowing enough time to make a decision. Two thresholds were obtained, one for each spatial frequency, and the order of testing was randomized across participants. All experiments took place in an audiometric sound-proof (Génie Audio, Québec, Canada) and dimly lit room, where each participant was tested in a single session of about 40 min.

**Results**

Spatial frequency discrimination thresholds for normally hearing and cochlear implant users are shown in Fig. 1. A two-way analysis of variance with group (controls, cochlear implant users) and visual condition (one cycle per degree, five cycles per degree) as within-subjects factor was carried out. Within-subject effects are reported according to the Greenhouse–Geisser’s correction. The analyses showed a significant interaction $F_{(1,32)} = 7.41, P < 0.01$, a main effect of frequency $F_{(1,32)} = 17.04, P < 0.01$, and a main effect of group $F_{(1,32)} = 43.45, P < 0.01$. Post-hoc analyses indicated that spatial frequency discrimination was significantly poorer in the cochlear implant users compared with the normally hearing group for both the lower ($t = 4.309, P < 0.01$) and the higher spatial frequency gratings ($t = 6.602, P < 0.01$). Regarding the significant interaction, the visual inspection of the figure suggests that the deficits were greater for the higher compared to the lower spatial frequency.

We also conducted a series of correlations on the clinical characteristics of the cochlear implant users that could have impacted visual performance. No significant correlations were found between spatial frequency discrimination thresholds and the (i) age at testing (low frequency: $r = 0.220, P > 0.05$; high frequency: $r = -0.017, P > 0.05$), (ii) duration of cochlear implant use (low frequency: $r = -0.192, P > 0.05$; high frequency: $r = -0.315, P > 0.05$), (iii) age at implantation (low frequency: $r = 0.228, P > 0.05$; high frequency: $r = 0.103, P > 0.05$), and (iv) auditory thresholds with the cochlear implant (low frequency: $r = 0.107, P > 0.05$; high frequency: $r = -0.172, P > 0.05$).

**Discussion**

The purpose of the present study was to assess low-level visual perception in cochlear implant users. For this, we measured spatial frequency discrimination, a fundamental building block of visual perception. Participants with a cochlear implant, who had experienced a prolonged period of progressive hearing loss since infancy, showed significant reductions in spatial frequency discrimination for both low-range and the mid-range spatial frequencies. Cochlear implant users were half as sensitive as the normally hearing controls on the discrimination task. The results suggest that auditory deprivation leads to deficits in spatial frequency discrimination and that these changes remain after the restoration of hearing with the cochlear implant.

Several studies suggest that deafness alters visual perception. On the one hand, there appears to be an enhancement in the perceptual abilities when higher-level visuospatial or peripheral tasks are performed [1,3,6,7,8]; on the other, there is a reduction in perceptual abilities when low-level visual tasks are performed. Our results agree with those from studies on deafness. Specifically, when compared with normally hearing individuals, the participants with a cochlear implant showed a reduction in spatial frequency discrimination of about 55%. This is consistent with the ‘deficiency theory’ that proposes that the loss of one sensory modality disrupts the development of another [19,20]. Another possibility that could explain why our participants have deficits in spatial frequency discrimination, is that the restoration of hearing in this group of deaf participants might overcome any visual gains associated with reorganization. Ultimately, our findings could be interpreted as suggesting that the normal development of the auditory modality is critical for the normal development of certain aspects of visual function.

The visual deficits reported in the present study do not seem to be related to any of the clinical characteristics of our participants, including the age at which the cochlear implant was received or the number of years the participants had used their cochlear implant. This is surprising, given that there is evidence of better clinical outcomes for individuals who had shorter periods of deafness before
abilities, with their reading proficiency rarely exceeding perception. Most deaf teenagers have a delay in reading important for fine visual analysis such as reading and scene perception. It is well known that spatial frequency discrimination is mature by 10 years of age [25]. The participants in the present study were implanted at an age <0.001. Examples of the low and high spatial frequencies are presented above the bar graph.

Cochlear implantation [21,22]. Children who received a cochlear implant before 3 years of age show significantly better results on tests of expressive and receptive language than children who were implanted after that age [23,24]. Therefore, it is possible that cochlear implant users with a shorter period of auditory deprivation also experience less cross-modal reorganization, which could ultimately lead to a better visual performance. There may be two reasons why we did not find any correlation to the periphery is enhanced in congenitally deaf individuals.

References
20 Wallace MT, Stein BE. Early experience determines how the senses will interact. J Neurophysiol 2007; 97:921–926.